

SCHOOL OF CIVIL ENGINEERING



JOINT HIGHWAY RESEARCH PROJECT

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THE EFFECTS OF BOTTOM
ASH UPON BITUMINOUS SAND
MIXTURES

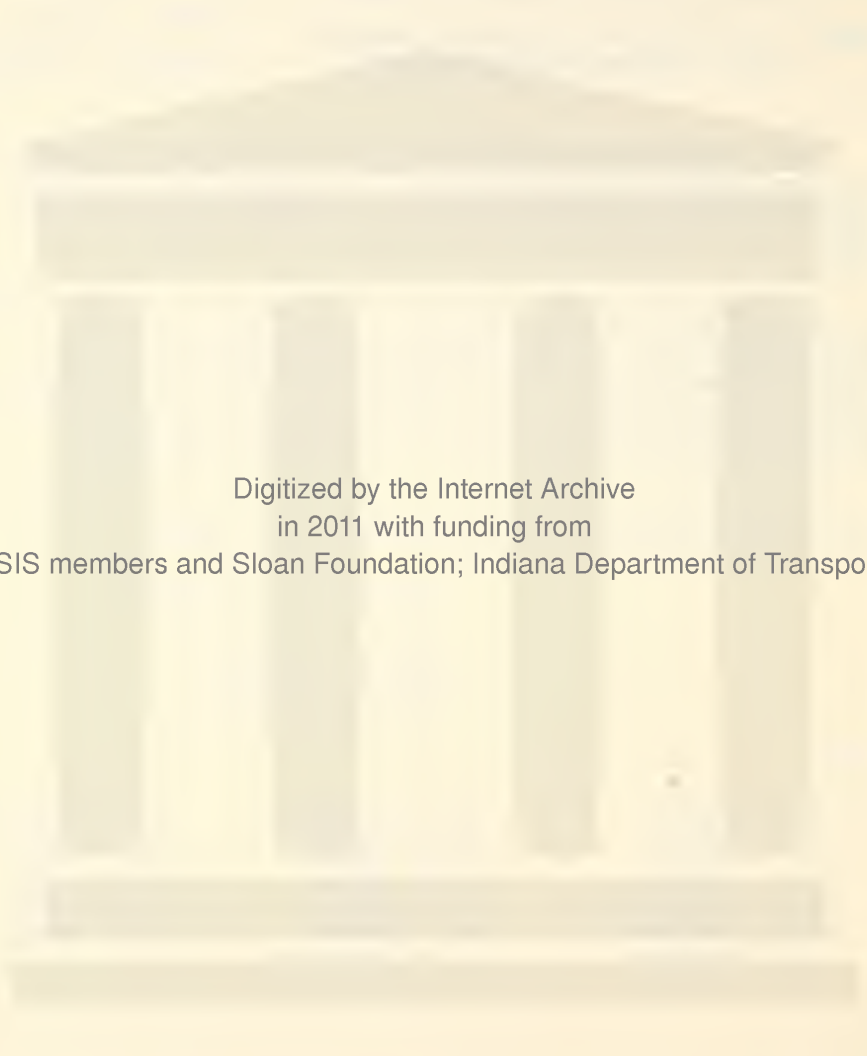
T. S. Shuler



PURDUE UNIVERSITY
INDIANA STATE HIGHWAY COMMISSION

THE EFFECTS OF BOTTOM ASH UPON BITUMINOUS SAND MIXTURES

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Final Report

THE EFFECTS OF BOTTOM ASH UPON BITUMINOUS SAND MIXTURES

by

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LIST OF SYMBOLS

- $\bar{A}$ = Aggregate Gradation Modulus (AGM)
- A_i = Multiplier constant corresponding to $\bar{d}$ for
determination of Aggregate Gradation Modulus
- $\bar{d}$ = Effective diameter; Aggregate Gradation Modulus
- $\Delta \Sigma \bar{A} \%$ = Percent difference of AGM values for before and
after compacted aggregate samples

ABSTRACT

Shuler, Thomas Scott. MSCE, Purdue University, May 1976.
The Effects of Bottom Ash Upon Bituminous Sand Mixtures.
Major Professor: Dr. Leonard E. Wood.

The growing depletion of high quality aggregate sources for use in highway construction necessitates the discovery either of new materials, or of methods to utilize marginal materials.

Bottom ash from coal burning power plants is abundant and offers properties lacking in conventional road aggregates. The vast differences in boilers, coal supplies, and combustion techniques lead to many varieties of ash by-products. Wide use of ash as an aggregate substitute has faltered due to a lack of definitive design parameters.

A laboratory study conducted on six bottom ash sources obtained throughout the state of Indiana attempted to physically characterize the materials. Tests included: Unit weight, ASTM C 29; Florida Bearing Test, Ind. 201-72; Hveem Centrifuge Kerosene Equivalent and Oil Ratio (24); Specific Gravity, ASTM C 127 and C 128; Dry Sieve Analysis, ASTM C 136; and a degradation analysis.

Mixtures of river sand, limestone, and two of the six sources of bottom ash were evaluated to determine the effect the ash had upon the performance of the mineral

aggregate when incorporated in a bituminous paving mixture. Tests used to evaluate their performance included: Florida Bearing Test on fine aggregate-ash mixtures prior to mixing with asphalt; Marshall Stability on specimens in the dry as well as the soaked condition; Hveem Stability and Cohesion; Skid Resistance; and a degradation analysis.

The presence of two characteristic ash classes were developed. The first did little to improve the skid resistance or the structural stability. The second class improved skid resistance but did not improve stability. Both classes of ash aided the mixtures in maintaining Marshall Stabilities when tested in the saturated condition.

The results of these tests provide information necessary for judging the suitability of paving mixtures containing bottom ash.

CHAPTER I INTRODUCTION

The Statement of the Problem

The diminishing supply of high quality natural aggregates for use in bituminous construction has had many detrimental effects associated with it (1). Among these are increasing numbers of skid prone surfaces, lack of structural stability, and higher construction costs. Concurrently, the depletion of the nation's oil reserve has directed attention toward the use of coal as an energy source, while concern over environmental protection has made it difficult to dispose of the ash by-product.

The combination of ash with inadequate natural aggregates would seem to offer a means for the improvement of overall performance of a bituminous paving mix with respect to skid resistance and structural stability (5). In this light, it may be possible to utilize a previously marginal aggregate in pavement construction with the aid of a bottom ash material. This would not only improve overall performance, but allow use of local materials, thus saving transportation costs involved in shipping quality aggregates.

One problem associated with coal bottom ash is its variability. The type of ash produced is dependent upon

the type of coal and the process by which the coal is expended. Two types of bottom ash exist (6, 7). These two types are produced from two different processes, a wet bottom process and a dry bottom process. In the wet bottom process the hot ash is released from the boiler and quenched in a water bath. The dry process allows the ash to cool in air. Wet bottom ash, WBA, or boiler slag, is typically an angular, black or brown, glassy substance. Dry bottom ash, DBA, exhibits a more vesicular surface texture, usually a dull gray color, and is relatively friable when compared to wet bottom ash.

The conclusion that bottom ash could improve the performance of bituminous surfaces stems from the vesicular surface texture that dry bottom ash exhibits, and the highly angular, glassy characteristics wet bottom ash displays. By adding these properties to mixtures containing round, low-porosity sands, and polish prone limestones, respectively, improvement would seem likely.

Other materials, such as steel blast furnace slag, have already proven themselves advantageous in skid resistance surfaces. Blast furnace slag has the disadvantage of only being readily available where steel is manufactured. Bottom ash has an availability advantage since it is produced by every coal burning power plant.

Production of wet bottom ash amounted to 5 million tons in 1972, 75 percent of which was utilized. Use of

the wet bottom process seems to be declining in favor of the dry method (15). 1974 production of dry ash reached 10 million tons and by 1976 it is expected to be over 100 million tons. At the present time only about 15 percent of all dry bottom ash is utilized, most of it as fill material (15).

The benefits to be gained from exploring productive uses for bottom ash in highway construction stem from the conversion of a troublesome solid waste material into an aggregate additive that will enable many areas of the country to use available aggregates in pavement construction that will not meet current specifications. A specific example would be in the Kankakee Lake Bed region of northern Indiana. Northern Indiana Power and Electric Co. is in the process of constructing a large coal-fired power facility in this area. Large quantities of bottom ash could be utilized for bituminous construction purposes in a region deficient of adequate mineral aggregate.

Besides areas where aggregates for use in bituminous construction are lacking, it is now necessary for many areas which utilized crushed stone in past years to search for a new material. This stems from the fact that most crushed carbonate aggregates, limestone, in particular, tend to degrade under the action of traffic (40). This condition usually leads to a surface which is highly polished and lends itself to a very low skid resistance.

However, since this polishing occurs mainly with the fraction of particles greater than $\frac{1}{8}$ inch in size, a portion of this study utilizes a crushed limestone fine aggregate blended with various amounts of wet and dry bottom ash.

At the present time there is a lack of information concerning certain design parameters that are necessary in order for bituminous paving mixtures utilizing bottom ash to perform satisfactorily. The goal of this study is to provide the necessary information to enable the Indiana Highway Commission to utilize mixtures containing bottom ash more effectively.

Research Objectives

Five of the six bottom ash materials tested were wet bottom varieties, or combinations of wet and dry bottom. A material obtained at Purdue University was dry bottom ash. More mixture research was performed on this material since the trend in production seems to be toward dry ash.

Ash properties pertinent to bituminous construction include its role in asphalt stripping behavior, surface texture, shape, and its durability. Stripping is the removal of an asphalt film from an aggregate particle by the action of water, and durability is the resistance of the aggregate to degradation under the action of traffic. Since ash is widely variable due to combustion processes

and coal sources, its stripping, durability, shape and surface texture characteristics should also be variable.

Dry bottom ash exhibits a highly porous texture and lacks durability due to its inherently friable nature. Wet bottom ash is quite glassy and contains fewer air pockets than the dry type, and is more durable.

The Indiana State Highway Department Type IV aggregate gradation (27) was used in this study to compare performance of mixes containing various quantities of bottom ash. The ultimate objectives were to observe the effects of ash upon the skid characteristics of limestone mixes and upon the stability characteristics of sand mixtures. This gradation was selected since it is currently the most frequently used in Indiana as a skid resistant surface.

Characterization of the six ash sources as well as comprehensive measurements of mixtures of sand with ash and stone with ash in skid resistance, stability, and water sensitivity tests were accomplished. Two categories of ash appeared as the characterization procedure was completed. Public Service of Indiana (PSI) ash was most representative of one group, while the PURDUE ash, (PU), represented the second group. These two materials were combined, separately, with both the stone and sand aggregates.

Research Approach

Ash Characterization

The use of bottom ash in bituminous mixtures should be possible if determination of a method to eliminate sources of ash that would prove unsatisfactory in service can be found. The bottom ash sampled from the six state-wide locations were subjected to six physical characterization tests to determine basic differences among the materials. These tests and the information they provide are listed below:

1. Unit Weight, ASTM C 29 - Loose density
2. Florida Bearing Test, Ind. 201-72 - Bearing Capacity
3. Centrifuge Kerosene Equivalent and Oil Ratio - Absorptive capacity
4. Specific Gravity, ASTM C 127 & 127 - Mass density
5. Sieve Analysis, ASTM C 136 - Natural gradation
6. Degradation Analysis - Durability

In all but two cases the ash tested was representative of the material produced at the six locations. The Purdue and Stout aggregates contained excessive quantities of material passing the No. 200 mesh sieve. These quantities were 20 and 35 percent respectively. The author felt that removal of this material prior to characterization was justified since this quantity of fine material would be

removed before the ash could be utilized in construction. It should be noted, however, that the Sieve Analysis Test is representative of the natural gradation of the ash. The two sources noted above were scalped over a No. 200 screen to facilitate better correlation between these two and the remaining sources.

Mixture Design

The major portion of this study was concerned with the evaluating of the performance of bituminous paving mixtures containing various quantities of bottom ash. Two aggregates were involved: a terrace sand and a limestone, and two sources of bottom ash: a dry bottom ash (PURDUE) and a wet bottom ash (Public Service Indiana). Mineral aggregate and ash mixtures were subjected to the Florida Bearing Test prior to adding asphalt to give an idea of premix strength reinforcement due to the ash. Design asphalt contents were first approximated using the Hveem CKE procedure. These approximations were verified by using Marshall and Hveem stability techniques. The Marshall Method of compaction was utilized in all cylinder fabrication. An AE-60 mixing grade emulsion was used as the binder material for all mixes. Laboratory testing used to evaluate performance of the mixtures included Marshall Stability, Hveem Stability, Hveem Cohesion, density and voids determinations, skid

resistance via the British Portable Tester, the Asphalt Institute Water Sensitivity Test, and a degradation test.

The water sensitivity test evaluated four parameters: the Marshall Stability after 24 hours at 140°F (60°C) in air, Marshall Stability after 24 hours at 140°F (60°C) in water, the percent retained stability, and the percent absorption after 24 hours in 140°F (60°C) water.

CHAPTER II LITERATURE REVIEW

In a study prepared by Witczak, Lovell, & Yoder (1), potential availability of high quality construction aggregates was found to be of a limited to severe nature in about one-third of the 48 contiguous United States. They utilized a questionnaire which allowed the states to indicate the nature of their respective quality aggregate availabilities. A four-level rating scale indicated the nature of the local aggregate supply ranging from "abundant-to-adequate down to 'severe problem'." It is interesting to note that approximately 90% of Indiana was rated "adequate to limited" in aggregate availability.

Concurrently, several studies (3, 8) have shown that total ash production in the U.S. has taken a threefold increase in the years from 1955-1971, i.e., 15,000,000 tons in 1955 and 43,000,000 tons in 1971. In 1974 the annual production of dry bottom ash (DBA) alone was 10,000,000 tons but by this year, 1976, is expected to exceed 100,000,000 tons (15). Dry bottom ash varies in quality and gradation. For this reason their utilization as construction aggregates has lagged production extensively (2, 3, 8, 15). Some progress has been made to put DBA to use, however (4, 5, 8).

Among highway departments that include ash as a construction material are Illinois, New Jersey, Ohio, and W. Virginia (10, 11, 12, 13). These agencies limit the use to only wet bottom materials as aggregates, however. The specifications describe the material and its limitations from the very general statement of Illinois; "... hard, angular by-product of the combustion of coal in wet-bottom boilers," to the more exact description of New Jersey and Ohio; "... Unit Weight not less than 85 lb/cu. ft., dry loose measure ... specific gravity not less than 2.80, 1.2% maximum absorption in cold water....," one-sized, ranging mainly between No. 4 and No. 30 screens, "Sodium Sulphate soundness loss not greater than 5%."

The utilization of bottom ash from local coal burning electric utilities as an engineering material was evaluated in a study (4) conducted at West Virginia University. The investigators determined what effects the use of bottom ash would have upon paving mixtures with and without the addition of mineral aggregates. Their study included the uses of both wet bottom and dry bottom ash as aggregates. It was determined that densities for the wet bottom variety, when used in nonstabilized base courses, generally equalled or exceeded the required 95 percent of the laboratory maximum dry density which was 85 lbs/cu. ft. However, when the material dried it lost stability, and it was necessary

to keep it in a wet condition in order to operate construction equipment on its surface.

Marshall and Hveem Stabilities, in the same study, using dry bottom ash with no mineral aggregate, produced values of 1000 pounds in the case of the Marshall, with Hveem Stabilities exceeding 40. It should be noted that the dry bottom ash used in this study was only slightly absorptive and demonstrated saturated-surface-dry moisture contents of no more than a few percent, with a gradation as follows:

Sieve Size	1½"	¾"	#4	#40	#200
% Passing	100	97	70.3	23	4.5

A dramatic increase in skid resistance in surface mixtures composed of blends of river and limestone sand, fly ash, and wet bottom ash, was prevalent when comparing accident data before and after deslicking. The gradation of this blend is as follows:

Sieve Size	¾"	#4	#3	#16	#50	#200
% Passing	100	95	85	48	16	6

In recent years the Asphalt Emulsion Industry has promoted the use of hot emulsion sand mixtures for skid proofing purposes. The mechanism of thixotropy in the bituminous residue allows high asphalt contents to be used in the mixtures without the danger of flushing occurring. These fine aggregate materials produce a

sandpaper-like surface texture that offers skid resistance. The surface loses fine particles as traffic acts upon it, thus exposing new aggregate particles which allow a continuation of the skid resistant surface. This effect becomes minimized as traffic speeds increase and when water is introduced. Some attribute this to the hydroplaning phenomenon (16, 18).

Serafin (16) suggested that a method of correcting this effect might include constructing surfaces containing sharp aggregate particles that protrude through the surface making contact with the tire at high speeds. In one phase of a study conducted by this researcher $\frac{3}{8}$ -inch top-size limestone, at 10-25%, was used in conjunction with a sand-asphalt surface. The results after four years were good since the quantity of stone was minimal, thus making polishing of slight concern. The same study found that addition of mineral filler and asphalt should be kept slightly below optimum to attain satisfactory skid resistance.

Others (17) report that materials such as crushed volcanic scoria, a lightweight aggregate comparable to dry bottom ash, produce good skid resistant surfaces when applied as seal coats.

In Europe a great number of research and development projects, with experimental as well as existing roads, have observed the effects of different pavement elements

upon skid resistance. Some of the information gained from this work by Nakkel (18) of Germany follows:

1. An increase in void content results in an increase in skid resistance.
2. Changes in the type of binder ... did not improve skid resistance.
3. Limestone chips in the 2-5 mm range gave satisfactory skid resistance.
4. Crushed sand is recommended for use with natural sand in a 1:1 blend to obtain good results.

Nakkel also makes the distinction between surface macrotexture (profile) and microtexture (degree of sharpness) in pavements. He states that macrotexture is effective at higher speeds because of an increase in the tire tread's ability to remove water from the contact area, called "dynamic drainage." At low speeds, the tire contact time and area are greater, thus allowing adequate water removal. Microtexture allows the tire to remove the last thin film of water at any speed.

In a report prepared by a special HRB Task Group (19), an assessment of the skid resistance problem in the United States was studied. The 48 contiguous states, 9 Canadian Provinces, and the District of Columbia were the respondents to a questionnaire developed to determine if skid resistance was a problem in their area, and if so, what measures were taken to correct it. Some of the questions

and replies are as follows:

1. Are slippery pavements a problem of major, moderate, or minor concern?

Major, 22; Moderate, 24; Minor, 2.

Indiana: Moderate

2. Are you now measuring skid resistance? If yes, how long?

Yes, 35; No, 13.

Minimum, $\frac{1}{2}$ year; Maximum, 30 years;

Average, $6\frac{1}{2}$ years.

Indiana: $\frac{1}{2}$ year

3. What type(s) of skid testing equipment is used?
 - a. Skid trailer, 29, Indiana.
 - b. Portable tester, 15.
 - c. Stopping distance method, 11.
 - e. Decelerometer, 4.
 - f. Mu Meter, 3.
4. Is research in progress concerning slipperiness?

Yes, 30; No, 18.

Indiana: Yes.

5. Is skid test data used as a criterion for resurfacing or deslicking?

Yes, 32; No, 12; Not Applicable, 4.

Indiana: No.

6. Do you use accident data for detection or selection of slipperiness?

Yes, 42; No, 6.

Indiana: Yes.

7. Does your state produce aggregate types known to polish and become slippery?

Yes, 20; No, 27; No Answer, 4.

Indiana: some suspected.

If yes, do you restrict the use of these materials in pavement surfaces?

Yes, 10; No, 10.

Of the 20 states reporting polish susceptible aggregates, limestone was the most prevalent.

8. Do you specify certain materials for wearing surfaces to assure high skid resistance?

Yes, 17; No, 31.

Indiana: No.

9. What methods of resurfacing or deslicking are used to restore skid resistance?

a. 100% polish resistant aggregate: 14

b. Blends of polish and polish resistant aggregate: 11

c. Thin sand-asphalt overlays: 18

d. Thin asphalt concrete overlays: 35 (Indiana)

e. Epoxy-silica sand: 3

f. Slurry seals: 16

- g. Synthetic aggregates: 10
- h. Seal coats (surface treatments): 37 (Indiana)

CHAPTER III DESCRIPTION OF EXPERIMENTAL MATERIALS

Six different bottom ash materials and two mineral aggregates were examined in this study. The ash materials consisted of four wet bottom products, a dry bottom ash, and a source which was a combination of both wet and dry. The ash ranged in character from gray, friable and porous to black, durable and glassy.

Sampling of the bottom ash was accomplished with the assistance of Professor Robert Jacko of the Purdue Environmental Engineering Department. Dr. Jacko's project was involved with five coal fired power plants throughout Indiana. This travel made it convenient to obtain bottom ash samples from the plants his crew visited.

The bottom ash, after various crushing processes, was usually transferred to storage pits by means of a slurry through a closed conduit. The only exception was the Purdue material which was transferred to storage by truck or rail car. Due to the slurry method, it was difficult to obtain a dry sample, at times. All materials, including the mineral aggregate, were sampled by hand-loading 20 gallon garbage cans. Care was taken to obtain as representative a sample as possible.

All materials were oven dried before testing for 24 hours at 220°F (104.5°C) to remove any absorbed water.

The six sources of bottom ash were sampled from the following locations: Northern Indiana Public Service Company (NIPSCO), Michigan City; Indianapolis Power and Light, Elmer Stout Station (STOUT), Indianapolis; Alcoa and Southern Indiana Gas and Electric Company, Culley Station (ALCOA), Yankeetown; Public Service Indiana (PSI), Edwardsport; Indiana and Michigan Electric, Breed Station (BREED), Fairbanks; Purdue University Power (PURDUE), West Lafayette. Figures 1 through 6 are photographs of all of the ash materials and appear following the written description.

Ash Aggregates

ALCOA

This ash was obtained from the Alcoa and Southern Indiana Gas and Electric Company's Culley Station, at Yankeetown. The ash was produced from a Southern Indiana coal in a dry bottom furnace but was quenched in water from the molten state. Fly ash from the convection banks was sluiced to the ashpit and mixed with the bottom ash. Clinker grinders were employed to pulverize the ash prior to sluicing (33). The final product was a hard, durable material of dark gray color showing traces of red and yellow, with a dull surface appearance.

BREED

This ash was produced at Indiana and Michigan Electric Company's Breed Station near Fairbanks, Indiana. This material was produced from coal obtained from the Shinook Mine in Southern Indiana. The wet bottom slag was crushed in clinker grinders prior to sluicing (34). The gradation was very one-sized. Angular, black, very glassy aggregate was produced with high density and low porosity.

NIPSCO

Northern Indiana Public Service Company at Michigan City was the producer of this ash which was manufactured in wet bottom furnaces from coal obtained in Illinois at the Ziegler Coal Company (35). A shiny, dark gray to black, low porosity, and relatively dense material was obtained.

PSI

Public Service Indiana, at Edwardsport, was the source of this bottom ash. This material was chosen to be one of the ash products utilized in the mix design portion of this study. This material had virtually the same specific gravity and unit weight as the BREED and was also similar in appearance.

STOUT

This material originated from the Elmer Stout Station of Indianapolis Power and Light, Indianapolis. The bottom

ash was stockpiled with the fly ash effluent from the smokestacks much like the ALCOA material. The appearance of this ash was intermediate between wet and dry bottom ash. This was due to simultaneous operation of both wet and dry processes at the plant. Two wet bottom and three dry bottom furnaces contributed ash to a single ash pit at this facility. Clinker grinders were utilized upon the product of Southern Indiana Coal (36). This ash exhibited a shiny luster coincident with a dull appearance. This material resembled the ALCOA ash since it had relatively high porosity and low specific gravity.

PURDUE

This was the only material that was exclusively dry bottom ash. It was sampled from the ash pile near Purdue University's South Power Plant. The specific gravity was low enough that some particles floated in water. The stockpile appeared red to brown in color, while individual pieces appeared light to dark gray. The large pieces were very friable and highly porous, and crushing these particles with the fingers was easily accomplished. The overall appearance was of a dull nature with local glassy regions.

As indicated previously, the ash products were sampled by hand at the storage sites and transferred by 20 gallon cans to the Purdue Bituminous Materials Laboratory for characterization.

The PSI and PURDUE materials used in the mixtures phase of the study were sized into logarithmic sieve series fractions.

The two sources of mineral aggregates used in this study were a terrace sand from the Western Indiana Aggregate Corporation gravel pit in West Lafayette, Indiana, and a crushed limestone obtained from the Erie Stone Company of Huntington, Indiana. These producers are listed as No.'s 2132 and 2211, respectively, by the Indiana State Highway Commission (22).

Mineral Aggregates

Natural Sand

The sand fractions of this study came from an outwash deposit of the early Wabash River, deposited during the Wisconsin glacial advance of the Pleistocene epoch (20). This sand and gravel contained mainly weathered sedimentary rocks--limestone and dolomite being the most prevalent. Small amounts of granite and quartzite made up the remaining two rock types.

Crushed Limestone

The geologic setting for this material was the Louisville limestone formation of the Silurian Series (28) whose physical properties were evaluated extensively by Pavolvich (21) pages 29 through 32. The sample was a gray to brown colored limestone in which chert nodules and argillaceous laminae were present (29, 30).

The exact ledge location of the source was not known to quarry personnel at the time the material was obtained (21).

Asphalt

A mixing grade emulsified asphalt was utilized in this study as the binder. The base asphalt consisted of an 85-100 grade asphalt cement obtained from the Rock Island refinery at Indianapolis. This cement is given the designation AP-3 by the State of Indiana. The asphalt cement was formulated into an AE-60 grade emulsion at the K. E. McConaughay laboratory in Lafayette, Indiana. The physical properties of these two asphalts are as follows:

AP-3

Penetration, 77°F, 5 sec., 100 gm.	96.0
Ductility, 77°F, 5 cm/min.	100+
Specific Gravity, 77°F	1.005
Solubility (CCl ₄), %	99.7
Viscosity, kinematic, 275°F, Cs	373.3
Softening Point, R and B, °F, (°C)	114.8 (46)
Penetration Index (by equation, see Appendix D)	-0.60

AE-60

Residue by distillation, %	72.0
Penetration of residue after distillation, 77°F, 5 sec., 100 gm	68.0

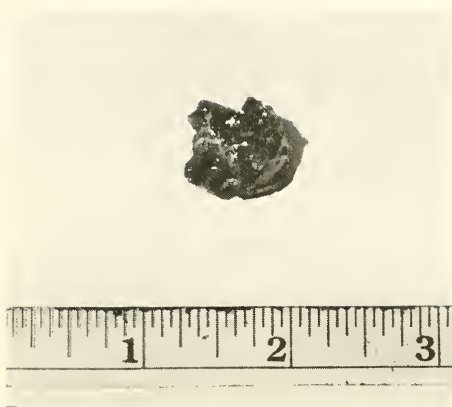


FIGURE 1 BREED ASH



FIGURE 2 PUBLIC SERVICE INDIANA (PSI) ASH



**FIGURE 3 NORTHERN INDIANA PUBLIC SERVICE
CO. (NIPSCO) ASH**



FIGURE 4 ALCOA ASH

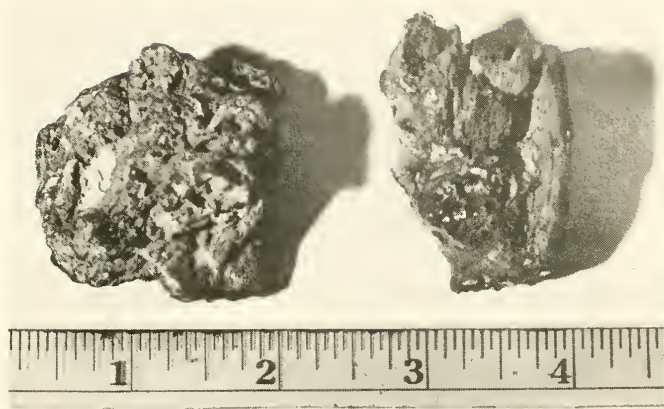


FIGURE 5 PURDUE ASH

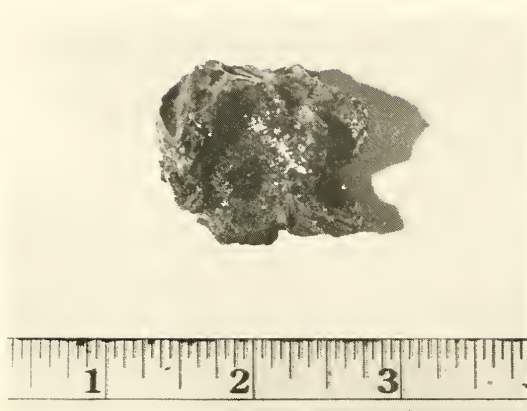


FIGURE 6 STOUT ASH

CHAPTER IV LABORATORY TESTING PROGRAM

Objectives

The objectives of the testing program were to evaluate and compare the effects of two types of bottom ash upon two types of mineral aggregates when used in a bituminous surface mixture. The PURDUE bottom ash was used to represent a typical dry bottom material, while the PSI ash represented the wet bottom type. The physical characteristics of the two materials were greatly different, and for this reason were judged satisfactory in representing the diversity found among ash products. The physical characteristics of the two mineral aggregates, crushed limestone and river sand, were also quite diverse.

The limestone was a structurally stable material when used in the Type IV gradation, but was suspected to exhibit poor skid resistance qualities due to potential polishing under the action of traffic. The sand, a good skid resistant surface in the type IV mixture, demonstrated relatively poor stability performance in the various laboratory tests.

The general premise was to determine whether the addition of bottom ash to these two aggregates could reduce

the undesirable qualities each possesses without sacrificing the favorable aspects.

The first step in the study was to conduct a characterization analysis of the ash materials. A means of classifying these materials was desirable since ash varies so greatly from source to source. Since time would not allow using each ash source in combination with the mineral aggregates this analysis was of great help in narrowing down the number of materials which would be utilized in the actual bituminous mixtures sequence of this study.

Ash Characterization Tests:

Description, Procedure and Apparatus

Unit Weight

ASTM C 29 (23): The jiggling procedure was followed for this test using a 1/10 cubic foot measure conforming to all requirements specified in the standard.

Florida Bearing Ratio

Ind. 201-72 (31): The method conformed to the ISHC Method of Test for Determining the Florida Bearing Value (FBV) of Fine Aggregate. The only exception to this method was that for initial compaction of the sample the Marshall Testing Machine was used in place of the Rimac Spring Tester. The Marshall Machine applies load at a varying rate through a movable stage operating at 2 inches per

minute. The Rimac spring device applies load constantly at 20 pounds per second. Comparison of the two procedures indicates that negligible differences exist between the methods when calculating bearing values (see Appendix B). Figure 7 is a photograph of the apparatus.

Centrifuge Kerosene Equivalent (CKE) and Oil Ratio (24)

The methods described for use in the Asphalt Institute's Manual Series No. 2 (MS-II) were followed in this test. The centrifugal force of 400 times gravity necessarily applied to the saturated samples of fine aggregate was attained by using the International Centrifuge Model CS at 1600 RPM.

Specific Gravity

ASTM C 127 and C 128 (23): These tests were followed for all materials, and in the case of the PURDUE ash, the specific gravity for each logarithmic fraction was determined. The test was performed in triplicate for each case.

Sieve Analysis

ASTM C 136 (23): The dry sieve analysis was conducted using a R0-Tap Testing Sieve Shaker manufactured by the Tyler Company, Cleveland, Ohio. The sieves conformed to specifications and were U.S. Standard Sieves of logarithmic series.



FIGURE 7 FLORIDA BEARING APPARATUS

Degradation Analysis

Standard 4 inch diameter by 2½ inch high Marshall specimens were fabricated using the ash gradation present in the field in combination with the material's optimum asphalt content as determined by the CKE and Oil Ratio tests. The sieve analysis of each specimen, fabricated in triplicate, was determined prior to mixing with asphalt. These mixes were batched and mixed using an AE-60 emulsion. The ash was heated to the 275°F (135°C) mixing temperature and the emulsion was applied cold. Mixing proceeded for 60 seconds using a Hobart Model N-50 mixer equipped with a whip attachment. The mixes were heated to 235°F and compacted in the standard manner by the Marshall Mechanical Compaction Device, with 75 blows per side of the sample. The Mechanical Marshall Hammer was manufactured by the Rainhart Company. The samples were allowed to cool to 140°F (60°C) and were then extruded from their respective molds. Upon cooling, density and voids determinations were conducted. The samples were then extracted of all asphalt by the method outlined in ASTM D2172, Method B in a Soiltest Vacuum Extractor Model AP-520, see Figure 8. The final sieve analysis of the aggregate portion of the mixtures was then performed.

The Aggregate Gradation Modulus (38) was calculated for each ash type and recorded to indicate the relative



FIGURE 8 VACUUM EXTRACTION APPARATUS

amount of degradation occurring in each specimen. An outline of the procedure followed to obtain the Gradation Modulus, ($\bar{A}$), can be found in Appendix A and in Chapter V prior to Tables 2 and 3.

Mixture Performance Tests:

Description, Procedure and Apparatus

Florida Bearing Test

Ind. 201-72: This test was conducted in the manner described in this chapter under the ash characterization section. The aggregates used were mixtures of ash and mineral aggregate and were evaluated for pre-mix strength. In addition to the two ash materials used for the major portion of the study, sand was tested in combinations of 10, 25 and 50 percent with the remaining four bottom ash sources.

Water Sensitivity (32)

Six standard Marshall cylinders were fabricated for each test by the mechanical hammer shown in Figure 9. Three of these cylinders were tested in the standard way by determining density and voids data prior to subjection to the stability test, see Figure 10. The specimens were held at 140°F for 24 hours in a forced air electric oven before testing. These specimens were designated as Group I. The three remaining cylinders were designated as Group II.



**FIGURE 9 MECHANICAL MARSHALL COMPACTION
HAMMER**

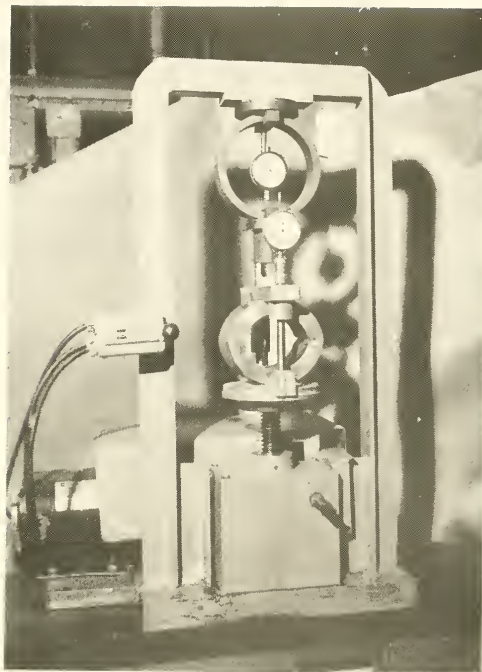


**FIGURE 10 MARSHALL STABILITY TESTING
MACHINE**

After density-voids determinations were carried out, the Group II specimens were subjected to 1 hour of vacuum at 30 mm of Hg. After the 1 hour period, 140°F (60°C) water was drawn into the vacuum chamber submerging the specimens and vacuum saturating them, see Figure 11. They were then transferred to a 140°F (60°C) water bath where they remained for 24 hours. One hour prior to testing for Marshall Stability the saturated surface dry weight of the cylinders was determined. The percent absorption was then determined as follows:

$$\% \text{ Absorption} = \frac{\text{Weight (SSD)} - \text{Weight (air)}}{\text{Weight (air)}} \times 100$$

After determining the Marshall Stabilities of the soaked cylinders, a comparison of these values with the values obtained from the air tested specimens led to a percent retained stability value.

$$\% \text{ Retained Stability} = \frac{\text{Group II Marshall Stability}}{\text{Group I Marshall Stability}} \times 100$$

Hveem Stability (24)

The Hveem Method of Mix Design was followed to determine optimum asphalt content. The Hveem Stability Test and Cohesion Test were used to verify CKE conclusions, and to also give a different evaluation of strength

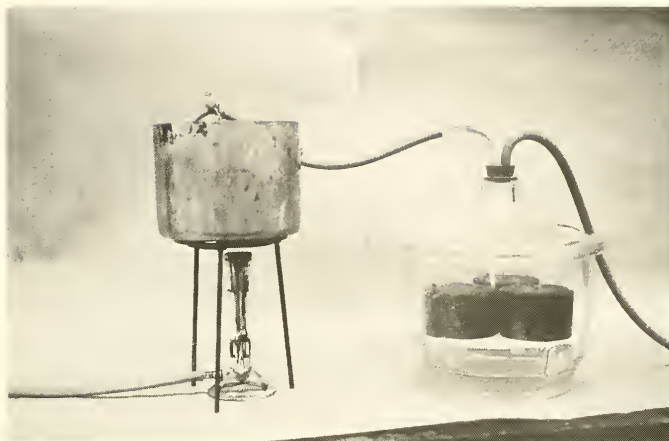


FIGURE 11 VACUUM SATURATION APPARATUS

differences among the various ash-mineral aggregate combinations than the Marshall Test could give.

The method was followed as per the Asphalt Institute's Method (24) with the exception of the compaction procedure. The Type IV mixture was so unstable under the kneading compactor that a competent sample was unattainable. The Marshall Hammer was used as a substitute.

Hveem Cohesion (25)

After the Hveem Stability was measured each specimen had its cohesion value determined. The test was performed in the standard way as described in the MS-II manual of the Asphalt Institute. In the case of multiple specimens, the average of all values was determined to evaluate the cohesiometer value.

Skid Resistance

ASTM E 303 (26): Skid specimens were selected from mixes in each group that demonstrated the highest Marshall Stabilities. The specimens measured 6.0" x 3.5" x 0.63". By obtaining the density of the specimen corresponding to the Marshall Test and dividing this value by the volume of the desired skid specimen, the total mix weight necessary to give this size specimen with the desired density was obtained. By using a steel mold two inches deep and applying load to the loose mix at 235°F (113°C) with a 3.5" x 6.0" x 1.37" steel block via a 50 kip Riehle

testing machine, the 5/8" thick skid specimens were obtained.

These specimens were held in place during the test with a steel mold 6.0" × 3.5" × 0.5". The specimens projected slightly above the mold so that no interference was possible between the testing device and the samples.

The standard method of test utilizing the British Portable Skid Tester as outlined in ASTM D301 was followed, see Figure 12.

Degradation

This test was identical to the degradation test performed on the bottom ash. In this case the procedure was used on selected samples of bituminous concrete composed of the various ash-aggregate combinations. The sieve analysis of all mixtures was the Type IV gradation prior to compaction.

The Aggregate Gradation Modulus (38) was utilized as the measure of degradation for the mixtures. The difference between the sums of Aggregate Gradation Moduli ($\Delta \Sigma \bar{A}$) of two test specimens indicates the relative amount of degradation occurring.

The more negative the difference in Aggregate Gradation Moduli are, the more degradation is occurring within that particular sample.

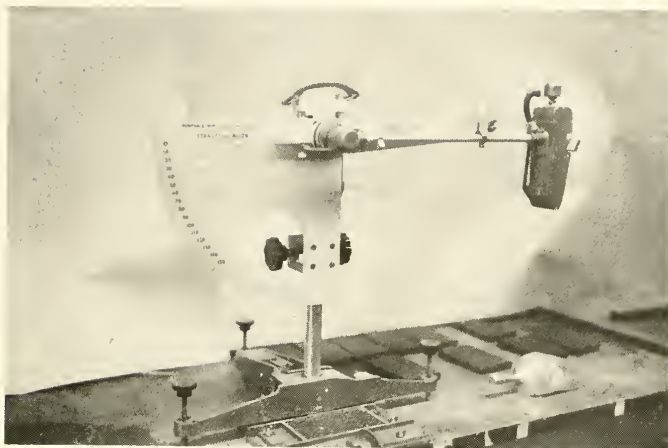


FIGURE 12 BRITISH PORTABLE SKID TESTER

CHAPTER V PRESENTATION OF RESULTS

The results of this research will be presented in two parts much like the previous chapters. The ash characterization will appear first, followed by the mix design segment. The results of all the ash characterization tests appear below in Table 1.

Table 1
Summary of Ash Characterization Results

	Ash	Florida Bearing Value	CKE	Median Bulk SP Gr	Sieve Analysis	Dry Density gm/cm ³	Avg. $\Delta\Sigma A$, %
Class I	BREED	53	1.40	2.80	One-Size	1.62	-0.68
	PSI	38	1.0	2.80	" "	1.57	-1.42
	NIPSCO	87	1.30	2.55	" "	1.40	-4.75
Class II	ALCOA	+100	4.6	2.35	Graded	1.63	-8.68
	STOUT	+100	5.1	2.35	"	1.66	-7.94
	PURDUE	+100	10.4	1.80	"	1.05	-7.50

Ash Characterization

Unit Weight

ASTM C 29: This test was performed to determine the loose density obtainable with dry ash. Values ranged from 1.05 to 1.66 for the PURDUE and STOUT materials respectively.

Florida Bearing Test

Ind 201-72: This test gives a good indication of the resistance of a fine aggregate to shearing action. The test was performed on all six ash products.

Values obtained range from a Florida Bearing Value (FBV) of 38 to values greater than 100, see Table 1.

The lowest values coincided with wet bottom materials having the smoothest surface textures.

Centrifuge Kerosene Equivalent and Oil Ratio

ASTM D 1560: A wide variation in CKE values coincides with the wide variation in FBV's. The materials with low FBV's had low CKE's. Values ranged from 1.00 for the PSI ash to over 10 for the PURDUE Material, see Table 1.

Specific Gravity

ASTM C 127, C 128: High Specific gravity values corresponded to materials having low FBV's and low CKE's. The Purdue ash had the lowest bulk specific gravities ranging from 1.37 to 2.12 for the $\frac{3}{4}$ "- $\frac{1}{2}$ " and 100-200 sizes

respectively. The effect of particle size upon the specific gravity may be seen in Figure 13. The highest bulk specific gravity values were obtained from the BREED ash at 2.79, see Table 1.

Sieve Analysis

ASTM C 136: Two gradation categories appear as a result of this test. The first category was a one-sized material to which the BREED, PSI and NIPSCO ash products belong. The second group was a more dense graded product to which the PURDUE, STOUT and ALCOA materials belong.

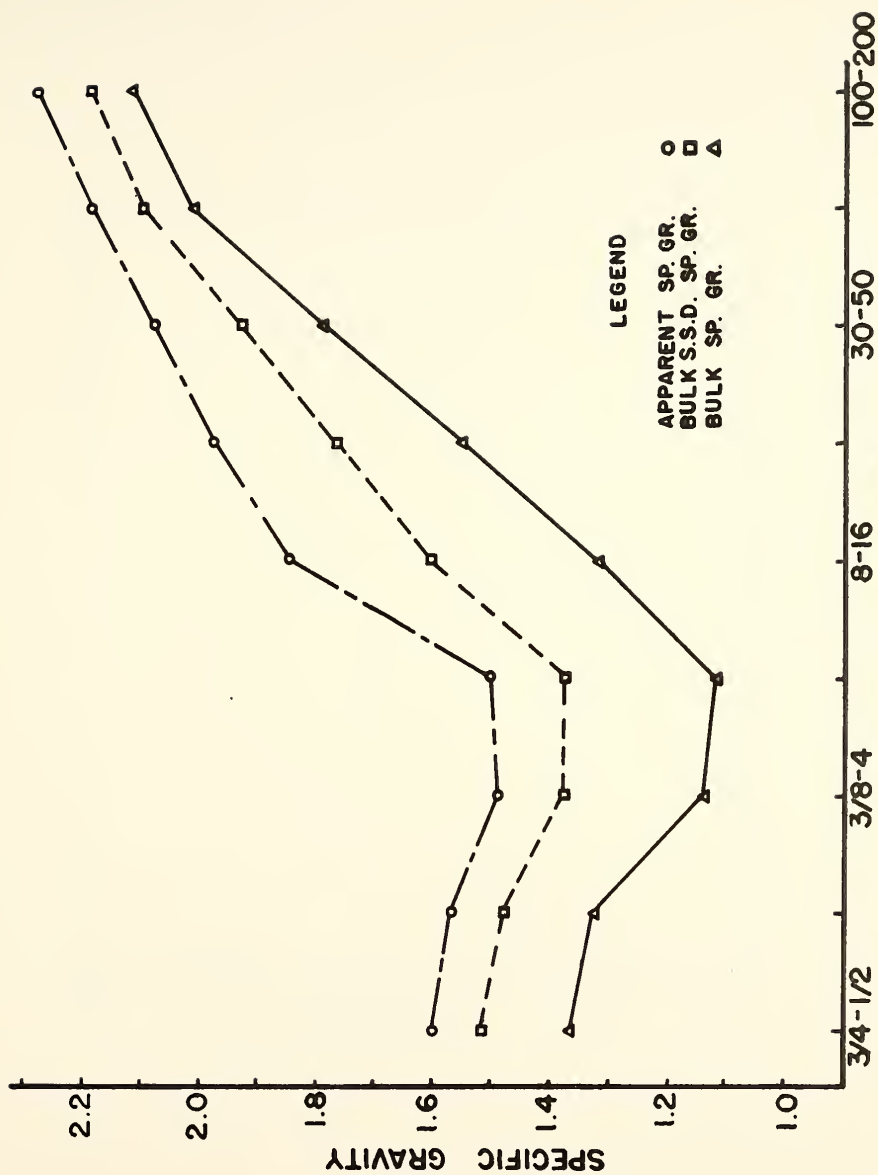
Sizes ranged from 3 inches to material that would pass the number 200 sieve. Gradation curves for the various ash materials are presented in Figures 14-19.

Degradation Analysis

This test measured the relative amount of degradation occurring among the ash products due to compaction by the Marshall Hammer. Two categories of degradation seem to be present. The BREED, PSI and NIPSCO materials have differences in Aggregate Gradation Moduli ($\Delta\bar{\Sigma\bar{A}}$) of between -0.68 and -4.75 (see Table 1). The ALCOA, PURDUE and STOUT materials have relatively higher (absolute value) $\Delta\bar{\Sigma\bar{A}}$ at between -7.50 and -8.68. The complete Degradation Analysis results for the ash are presented in Table 2.

The Aggregate Gradation Modulus ($\bar{A}$) is determined as follows:

**FIGURE 13 SPECIFIC GRAVITY vs. SIEVE FRACTIONS (LOGARITHMIC SERIES)
FOR PURDUE BOTTOM ASH**



SIEVE FRACTION
FIGURE 13

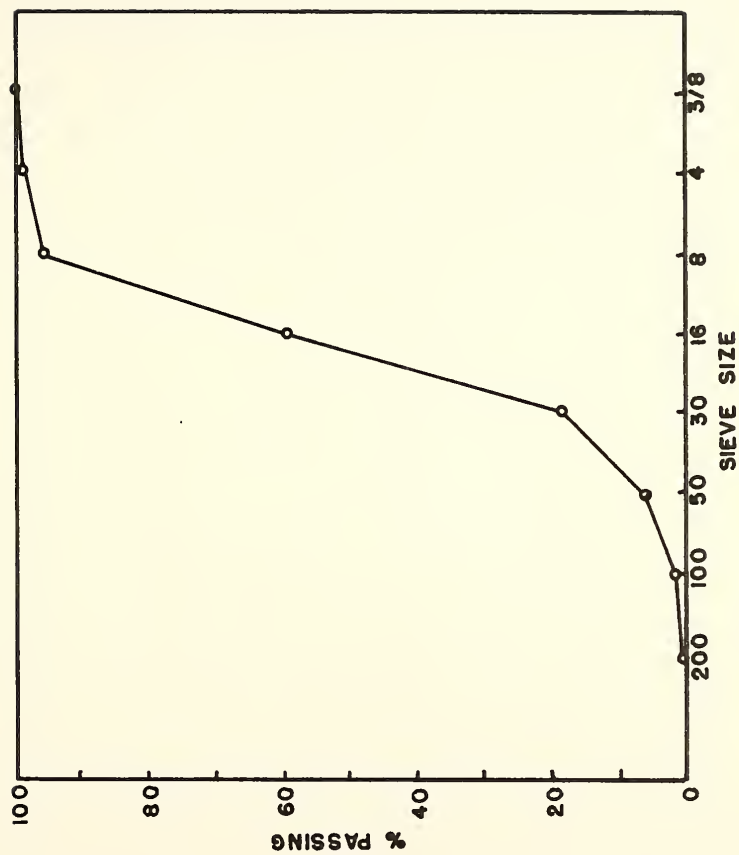


FIGURE 14 AVG. SIEVE ANALYSIS— BREED ASH

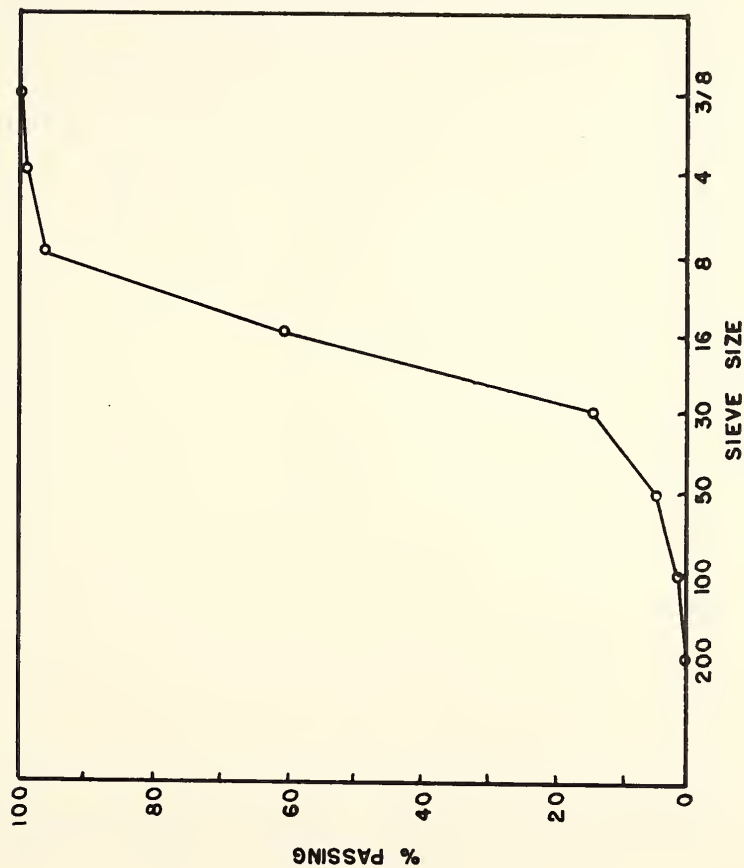


FIGURE 15 AVG. SIEVE ANALYSIS — PSI ASH

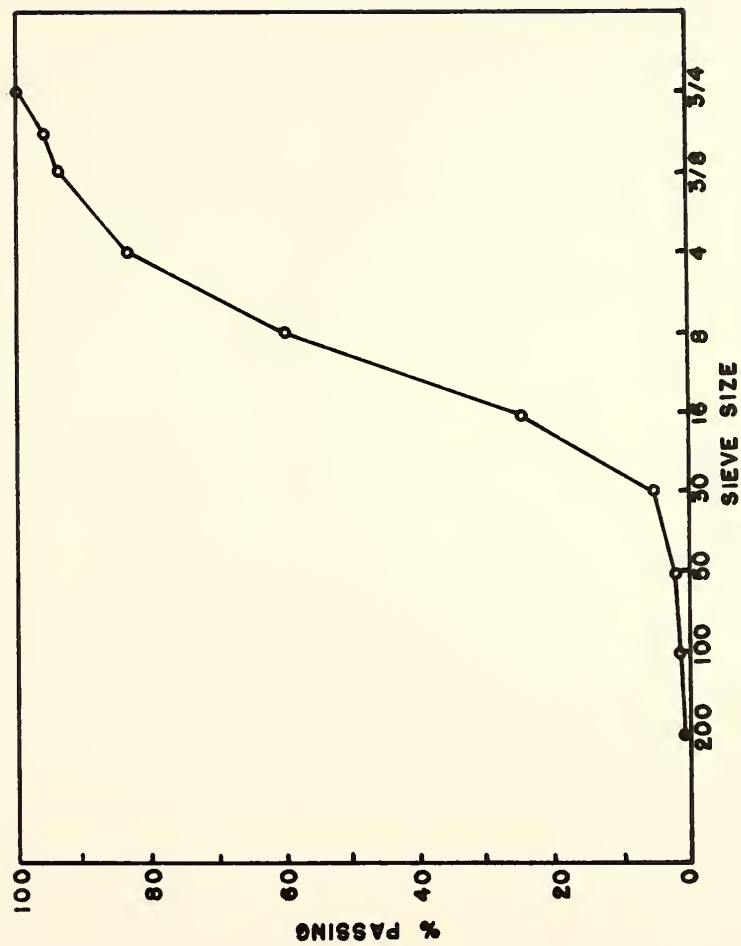


FIGURE 16 AVG. SIEVE ANALYSIS—NIPSCO ASH

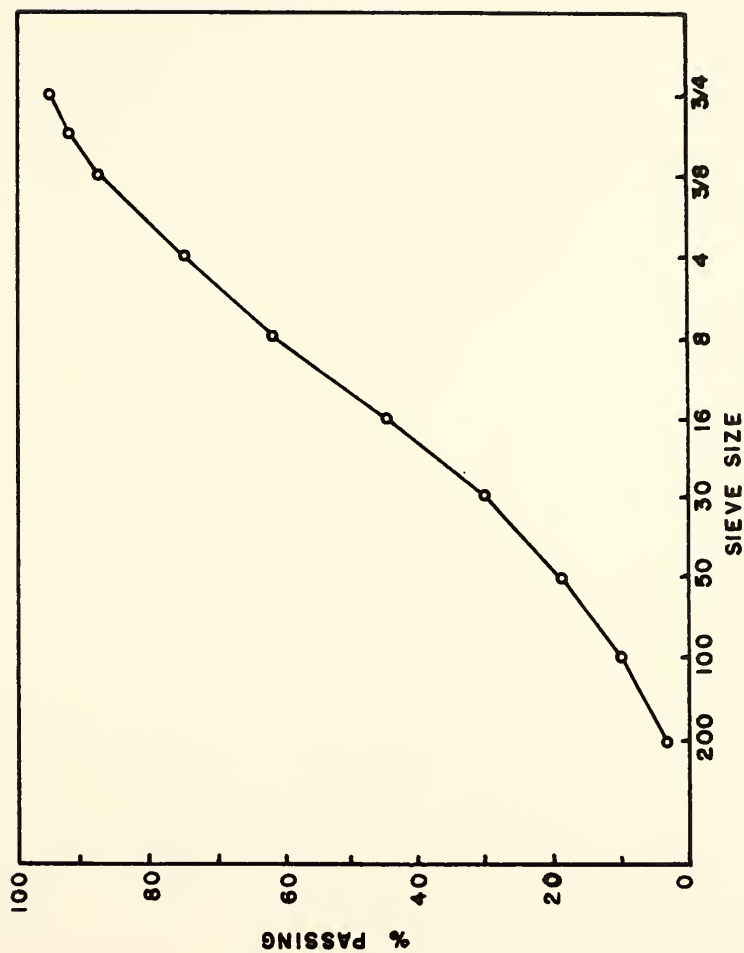


FIGURE 17 AVG. SIEVE ANALYSIS — ALCOA ASH

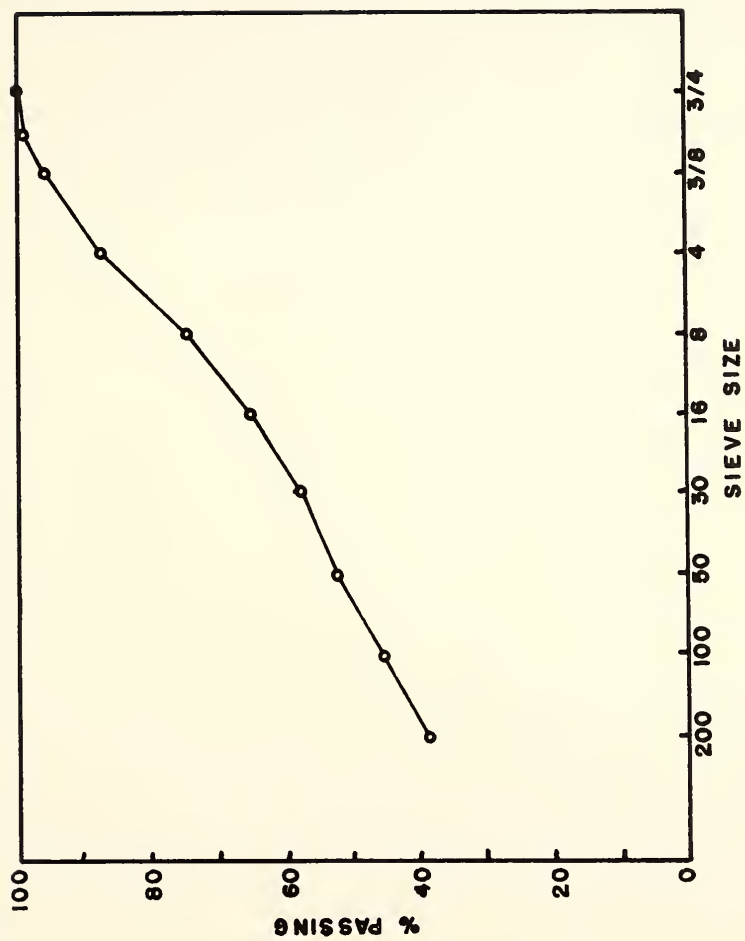


FIGURE 18 AVG. SIEVE ANALYSIS — STOUT ASH

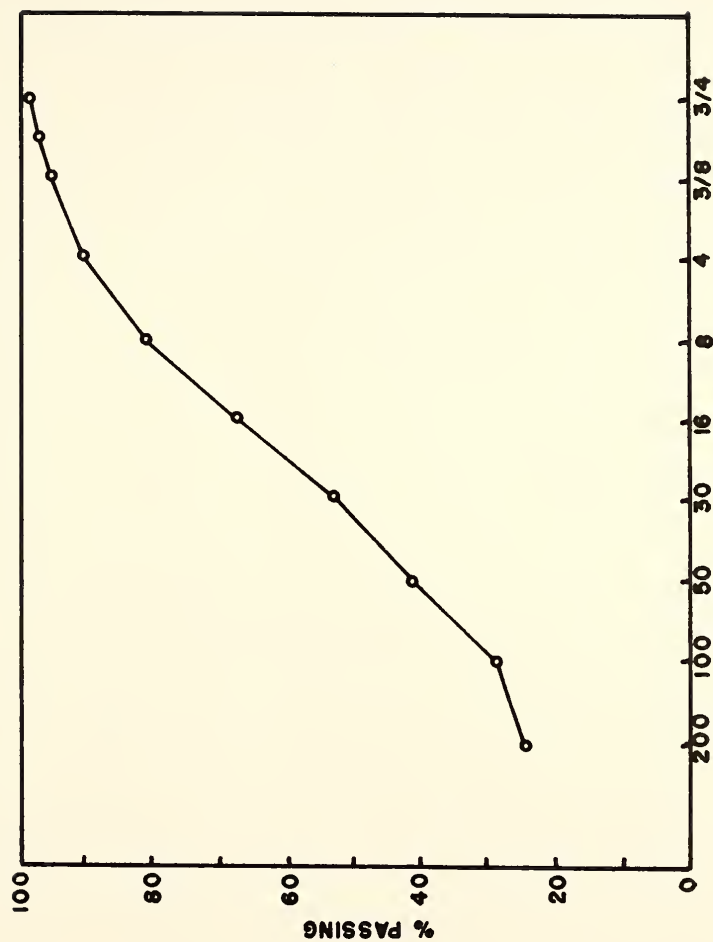


FIGURE 19 AVG. SIEVE ANALYSIS—PURDUE ASH

Table 2
Degradation Analysis Summary

Ash Specimens

Specimen	$\Delta\bar{\Sigma A},$ %	Average	Specimen	$\Delta\bar{\Sigma A},$ %	Average
B 1	-0.13	-0.68	AL 1	-7.13	-8.68
B 2	-0.55		AL 2	-9.22	
B 3	-1.35		AL 3	-9.69	
P 1	-0.56	-1.42	PU 1	-6.92	-7.94
P 2	-1.55		PU 2	-7.83	
P 3	-2.14		PU 3	-9.07	
N 1	-5.66	-4.75	S 1	-7.87	-7.50
N 2	-4.96		S 2	-5.36	
N 3	-3.63		S 3	-7.87	

Legend:

- B - BREED ash
- P - Public Service Indiana (PSI) ash
- N - Northern Indiana Public Service Co. (NIPSCO) ash
- AL - ALCOA ash
- PU - PURDUE ash
- S - STOUT ash

See Appendix A for outline describing procedure in obtaining $\Delta\bar{\Sigma A}$.

Find $\bar{d}$, the effective diameter for each gradation fraction between adjacent sieve sizes;

$$\bar{d} = \frac{0.4343(d_1 - d_2)}{\log \frac{d_1}{d_2}} \quad (d \text{ in mm})$$

Find a corresponding A_i value for each $\bar{d}$;

$$A_i = \frac{\log 54.8 - \log \bar{d}_i}{\log 2}$$

Determine the Aggregate Gradation Modulus ($\bar{A}$) by;

$$\bar{A} = \sum(A_i) \quad (\% \text{ by weight of each sieve fraction})$$

Table 3 contains $\bar{d}_i$ and A_i factors for the sieve series used.

Table 3
Tabulation of A_i and $\bar{d}_i$ Used to Determine $\bar{A}$

d_1	d_1 (mm)	d_2	d_2 (mm)	$\bar{d}_i$	A_i
1"	25.33	$\frac{3}{4}$ "	19.00	22.1	1.31
$\frac{3}{4}$ "	19.00	$\frac{1}{2}$ "	12.67	18.9	1.80
$\frac{1}{2}$ "	12.67	$\frac{3}{8}$ "	9.51	11.0	2.31
$\frac{3}{8}$ "	9.51	#4	4.76	6.85	3.00
#4	4.76	#8	2.38	3.43	4.00
#8	2.38	#16	1.19	1.72	5.00
#16	1.19	#30	0.60	0.86	6.00
#30	0.60	#50	0.30	0.43	7.00
#50	0.30	#100	0.15	0.21	8.00
#100	0.15	#200	0.07	0.11	9.00
#200	0.07	Pan	0.00	0.003	14.00

Mix Design

Cylinder designation code:

Apply to specimen identification in Tables 4 and 5.

Variable parameters:

1. Asphalt content, %
2. Sand or limestone, S or L
3. Ash content, %
4. Trial No., A, B, C, etc.; A - Marshall, Group I;
B - Marshall, Group II; C - Hveem Stability and Cohesion; D - Skid Resistance
5. Specimen No., 1, 2, 3, etc.; three specimens were fabricated for each trial.
6. Ash type: PU, PURDUE; P, Public Service Indiana

Therefore:

5.4S25B3P*

indicates:

5.4% Asphalt by Aggregate Weight

Sand

25% ash

Second Trial Series, usually Group II, Marshall

Third Specimen

'PSI' Ash

* If an alphabetic suffix is omitted, PURDUE ash is understood.

Note: Variable parameter code numbers 4 and 5, i.e., trial number and specimen number are omitted from the sample identification in Tables 4 and 5. These tables reflect average values for several tests.

Florida Bearing Test

Ind 201-72: This test was performed on mixtures of sand and all six ash products, results of which are presented in Figures 20, 21, and 22, as well as on limestone with PURDUE and PSI ash, Figures 23 and 24.

The FBV of the sand was 16.4. When tested with varying amounts of ash, the FBV of the mixture increased with increasing quantities of ash until the FBV of the ash was approached.

The FBV of the limestone was greater than 100. Adding the PURDUE ash, FBV 100, had no effect on the mixture's performance. The PSI ash had a FBV of 38. Adding this material to the limestone decreased the FBV of the resulting mixture.

Upon completing the evaluation of the aggregates involved in the research program, the testing of the aggregate-asphalt mixtures began. This segment of the program determined what effects the various ash fractions had upon the performance of the sand and limestone in the Type IV mix. The gradation of the Type IV mix as used in this study follows under the column labeled % Passing.

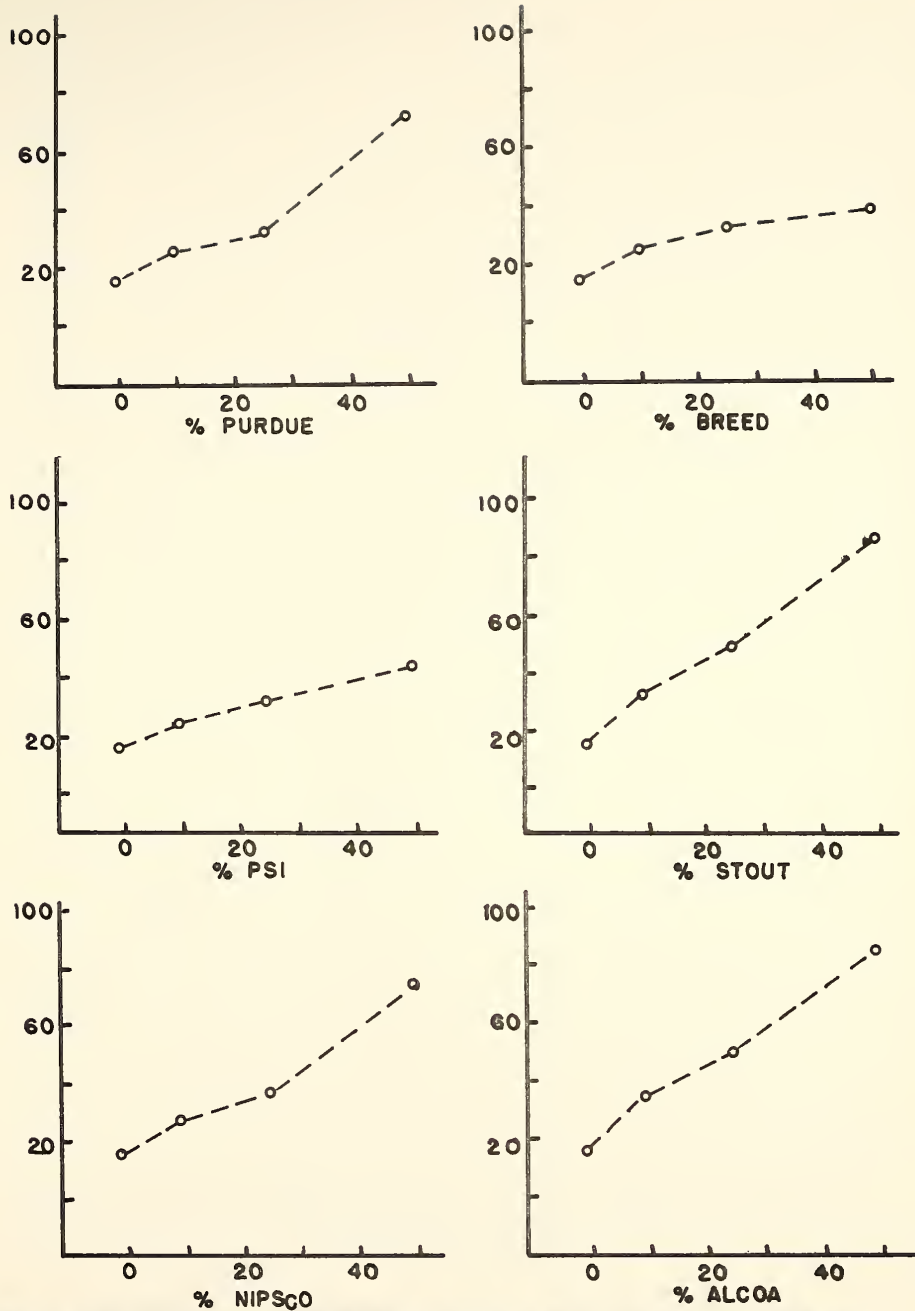


**FIGURE 20 FLORIDA BEARING VALUE, PSI VS. ASH CONTENT
SAND AND ALL ASH TYPES**

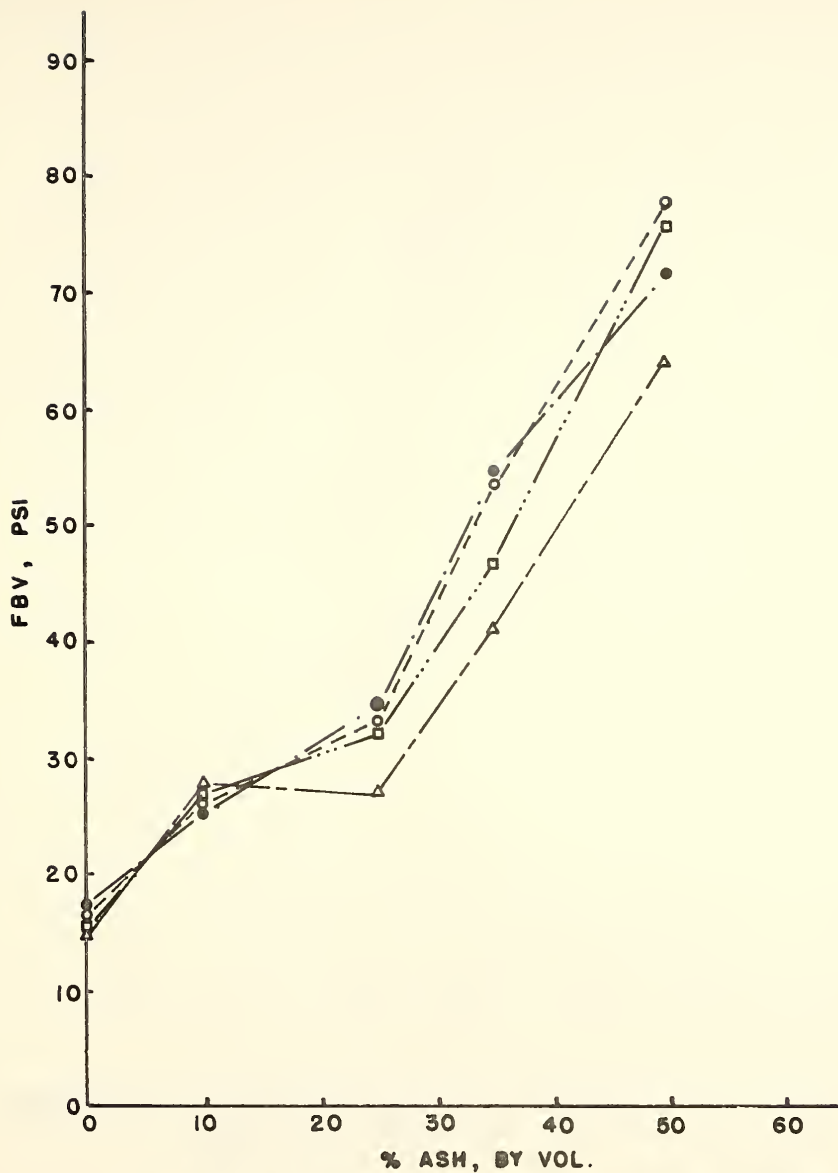


FIGURE 21 FLORIDA BEARING VALUE vs. % ASH
SAND AND PURDUE ASH

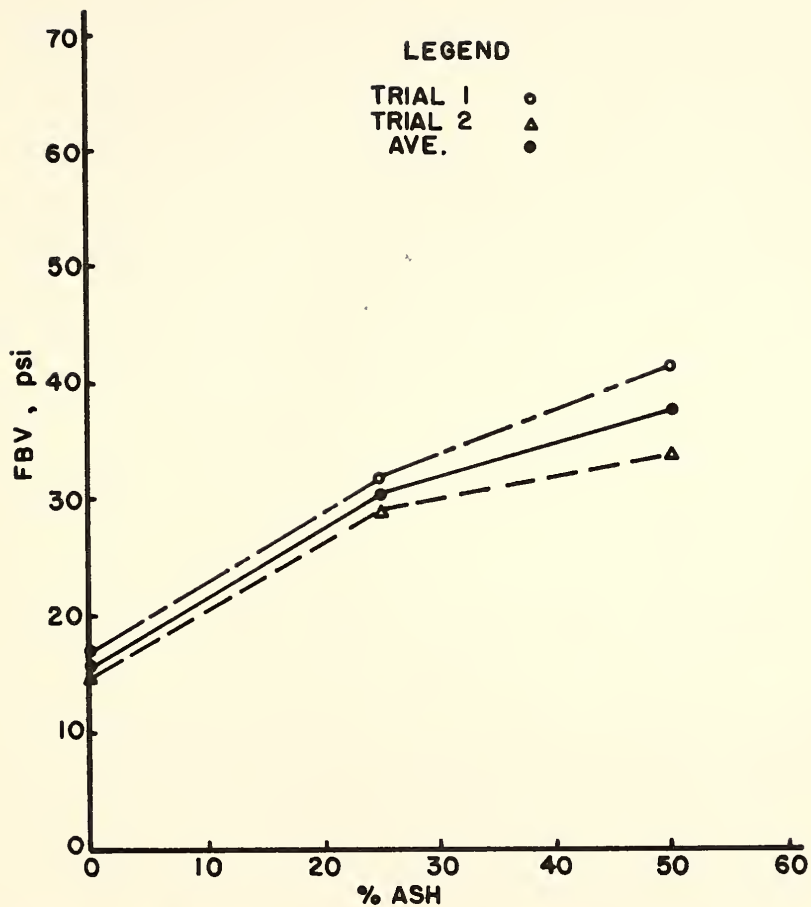


FIGURE 22 FLORIDA BEARING vs. % ASH
SAND - PSI ASH

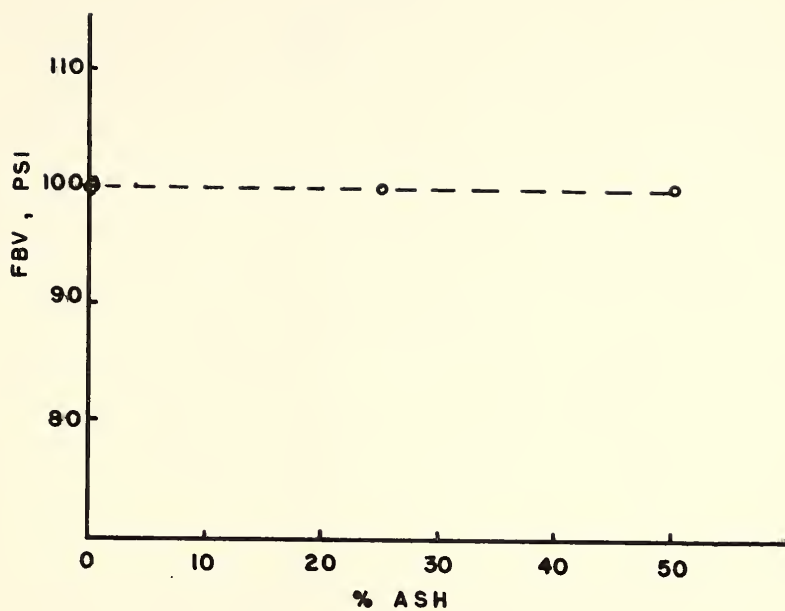


FIGURE 23 FLORIDA BEARING vs. ASH CONTENT
LIMESTONE-PURDUE

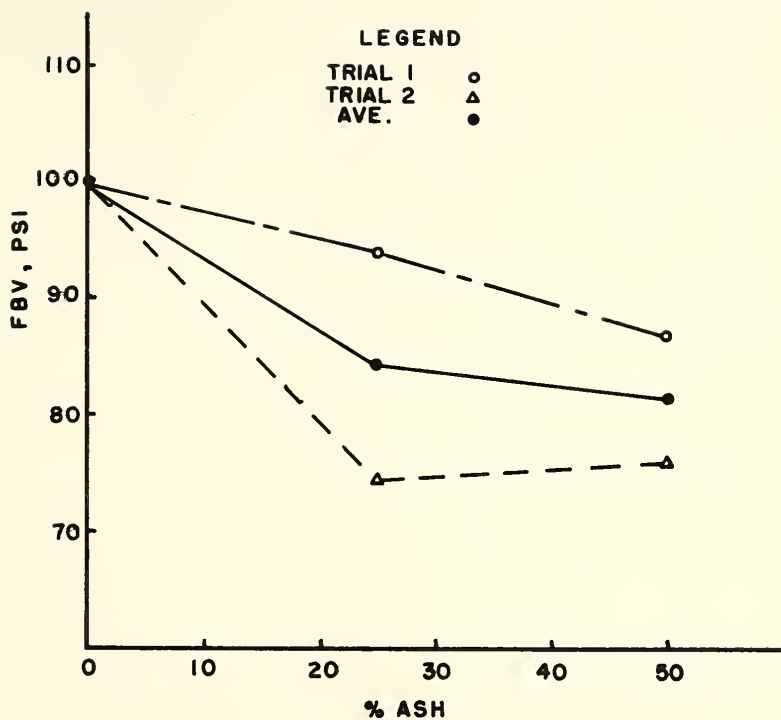


FIGURE 24 FLORIDA BEARING vs. ASH CONTENT
LIMESTONE-PSI

Indiana Type IV Gradation

<u>Sieve Size</u>	<u>% Passing</u>	<u>Specification Limits % Passing</u>
$\frac{3}{8}$ "	100	100
#4	98	97-100
#8	86	71-100
#16	65	50-80
#30	40	20-60
#50	20	5-35
#100	6	1-15
#200	0	0-5

The graph of this gradation is shown in Figure 25.

The ash was combined with the mineral aggregate in a manner such that the ash replaced an equal volume of the mineral aggregate, thereby retaining the same gradation. The volume replacements tested equalled 0%, 10%, 25%, 35%, and 50% for the sand and PURDUE materials and 0%, 25%, and 50% for the other three combinations of mineral aggregate and ash.

The sequence of aggregate-asphalt mixture tests is as follows:

Marshall Stability Group I

Water Sensitivity

- a. Density - Air Voids
- b. Marshall Stability, Group II
- c. % Retained Stability
- d. Absorption, %

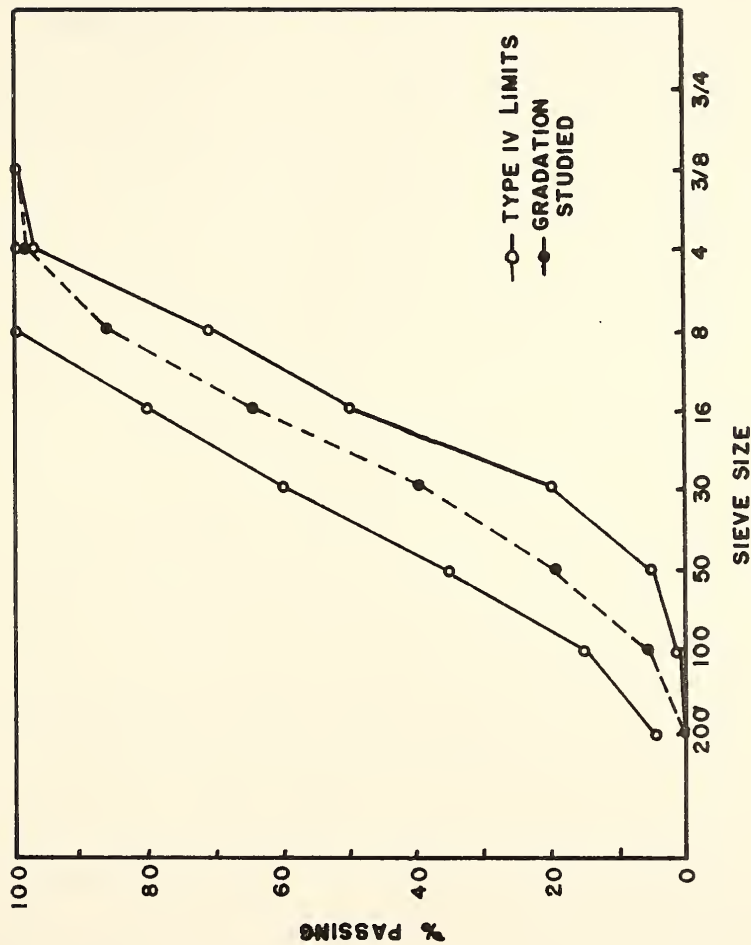


FIGURE 25 TYPE IV GRADATION

Hveem Tests

- a. Hveem Stability
- b. Hveem Cohesion
- c. Density-Air Voids

Skid Resistance

Degradation

Table 4 is a summary of the results obtained from all of the mixture tests.

The trends in stability data mentioned in the following descriptions of the Marshall and Hveem tests are indicative of maximum values obtained since asphalt content is varying as well as ash content.

Marshall Stability and Flow, Group I

ASTM D 1559

Sand and PURDUE Ash. The stabilities obtained from this test do not indicate a definite trend. While a small increase in overall stability is evident, it is not significant. The stability values seem to range between the upper 400 and upper 500 pound values.

The flow values were all relatively low and fluctuated very little.

Table 4 indicates that the asphalt content required to maintain maximum stability rises with increasing ash quantities, but at a moderate rate.

Table 4

Mixture Test Summary

Sample	Water Sensitivity Test								Marshall & Hveem Tests	Skid Resist- ance	Degrada- tion Test
	Average Group I Marshall Stab. lbs	Average Group II Marshall Stab. lbs	Average Group I Flow Units	Average % Retain. Stab.	Average % Absorp- tion	Average % Air Voids	Average % VMA	Average Unit Weight Pcf			
4.4S0	438.2		3.9			14.2	23.4	129.5			
5.4S0	461.5		4.0			11.8	22.5	131.5			
5.9S0	462.6		3.5			10.6	22.5	132.3			
6.4S0	507.1	268.8	4.2	53.0	6.4	9.9	22.6	132.5	66		
6.9S0	412.6		4.6			8.9	22.7	133.2			
7.4S0	384.6		5.0			8.1	22.8	133.6			0.0
4.9S10	335.2		3.6			14.0	23.5	124.6			
5.9S10	383.9		4.8			12.0	23.4	126.0			
6.4S10	474.1		5.4			10.9	23.1	127.0			
6.9S10	480.1		4.4			9.5	22.8	128.1	64		
7.4S10	477.1		5.9			9.0	23.0	128.2			-3.5
7.4S10	450.1		4.9			7.9	23.0	129.0			
6.3S25	549.8		5.6			13.7	24.8	117.4			-2.9
6.8S25	585.4	352.5	5.9	91.5	10.5	12.5	24.7	118.2	72		-3.3
7.3S25	560.8		6.3			11.3	24.3	119.2			-3.5
6.5S35	457.0		4.4			13.6	25.3	111.9			
7.0S35	472.7		4.6			14.4	25.3	112.5	75		
7.5S35	496.5		4.8			12.3	25.0	113.4			-3.5
7.8S50	500.6		5.9			14.7	26.7	104.1			-4.0
8.3S50	512.2	511.9	5.8	99.9	14.8	13.7	26.7	104.7	80		
8.8S50	473.2		6.5			13.7	27.2	104.3			

Note: See page 56 for an explanation of the code used to identify the samples.

(continued)

Table 4
(continued)

Sample	Water Sensitivity Test										Hveem Tests		Marshall & Hveem Tests	Skid Resistance	Degradation Test
	Average Group I Marshall Stab. lbs	Average Group II Marshall Stab. lbs	Average Group I Flow Units	Average % Retain. Stab.	Average % Absorption	Average % Air Voids	Average % VMA	Average Hveem Stab.	Average Hveem Cohes.	Average Unit Weight Pcf	Average BPN Units	Avg. $\Delta\bar{\Sigma}\bar{A}$			
5.1S25P	220.7	161.4	4.4	73.1	7.9	14.1	24.4	22.0	64.4	130.3	67	-2.0			
5.6S25P	196.2		4.5			13.2	24.3			131.1		-3.4			
6.1S25P	193.7		4.2			12.5	24.4			131.3					
3.7L0	2004.1		5.0			9.8	17.3			131.3					
4.7L0	1876.1	1725.5	6.2	91.9	8.5	8.0	17.5	36.0	145.5	132.1	72	-5.8			
5.7L0	1888.3		6.8			5.0	16.7			134.5		-4.2			
6.0L25	1065.0	975.6	5.9	91.6	12.0	13.6	23.9	33.0	107.5	113.1	84	-7.1			
7.0L25	1032.7		6.1			11.5	23.5			114.8					
8.0L25	971.9		6.4			10.1	23.7			115.5					
6.7L50	252.3		7.4			15.7	25.8			100.7		-6.2			
7.7L50	834.2		7.5			14.1	25.6			101.8		-7.4			
8.7L50	855.3	817.0	7.4	95.5	14.2	12.0	25.3	25.5	103.0	103.4	88				
4.7L25P	848.2	71.1	4.8	100.0	8.2	14.9	24.4	27.0	102.1	129.8	74	-4.1			
5.7L25P	833.8		5.7			13.1	24.5			130.8					
6.7L25P	787.9		6.3			11.1	24.4			132.3					
3.7L50P	460.3	428.4	5.0	84.7	9.4	18.4	25.3	20.5	83.6	128.4	75	-4.9			
4.7L50P	505.5		5.2			15.6	25.1			131.0					
5.7L50P															

(continued)

Table 4
(continued)

Specimen	Average Hveem Stability	Average Hveem Cohesion
2.0S0	19	64.0
3.0S0	21	
4.0S0	23	
5.0S0	24	
5.4S0	25	
6.0S0	19	
8.0S0	22	
3.0S10	20	
4.0S25	23	64.8
5.0S25	21	
6.0S25	20	
7.0S25	20	
11.0S25	19	
4.0S35	16	68.4
7.0S35	20	
3.0S50	18	65.4
5.0S50	17	
6.0S50	19	
8.3S50	19	
9.0S50	18	
10.0S50	17	
15.0S50	16	

Figure 26 graphically demonstrates the relationship between stability, asphalt content, and ash content in three dimensions. Following this graph are Figures 28 through 31 indicating the trend in Marshall design values with respect to asphalt and ash content. A contour graph of Marshall Stabilities showing the relation of asphalt to ash content is depicted in Figure 27.

Sand and Public Service Indiana (PSI) Ash. A definite trend is apparent in this series. The drop in stability is from a maximum of 507 lbs at 0% ash content to a maximum value of 220 lbs at 25% ash content.

Flow values remained approximately constant at 4.2 to 4.4 hundredths of an inch. Figure 32 displays Marshall design values as affected by asphalt and ash content.

Limestone and PURDUE Ash. The limestone has a Marshall Stability of more than 2000 lbs with 0% ash content. As quantities of ash are introduced this value decreases until at 50% ash content, the stability is 850 lbs.

Flow values increased from 5.0 hundredths of an inch at 0% to 7.4 hundredths of an inch at 50% ash content.

Another three dimensional graph of Marshall Stability, asphalt content, and ash content is presented in Figure 33. Figures 35 through 38 represent Marshall design values vs. asphalt and ash content. See Figure 34 for a representation of Marshall Stability contours as influenced by asphalt and ash content.

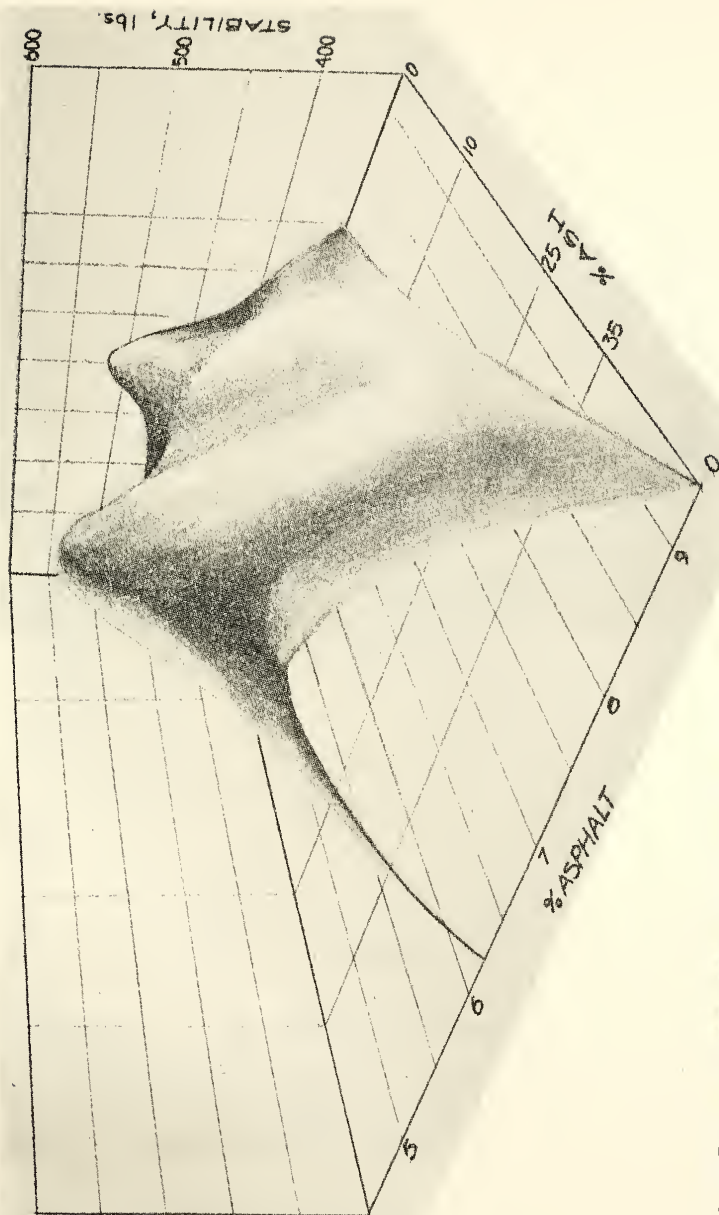


**FIGURE 26 MARSHALL STABILITY vs.
% ASPHALT vs. % ASH FOR
SAND AND PURDUE ASH MIXTURES**

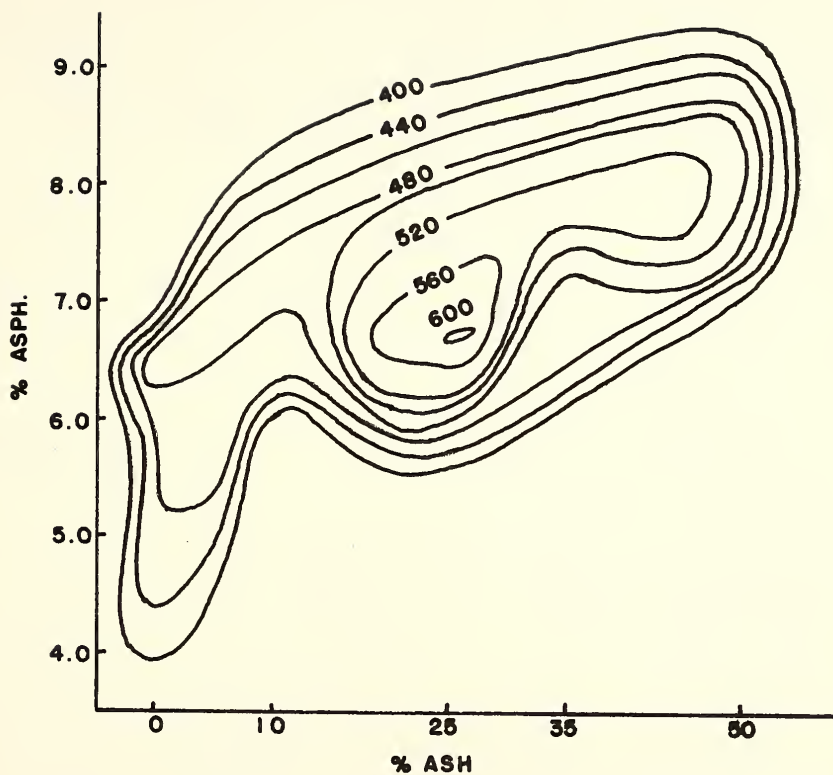


FIGURE 27 % ASPHALT vs. % ASH
MARSHALL STABILITY CONTOURS IN lbs.
SAND — PURDUE

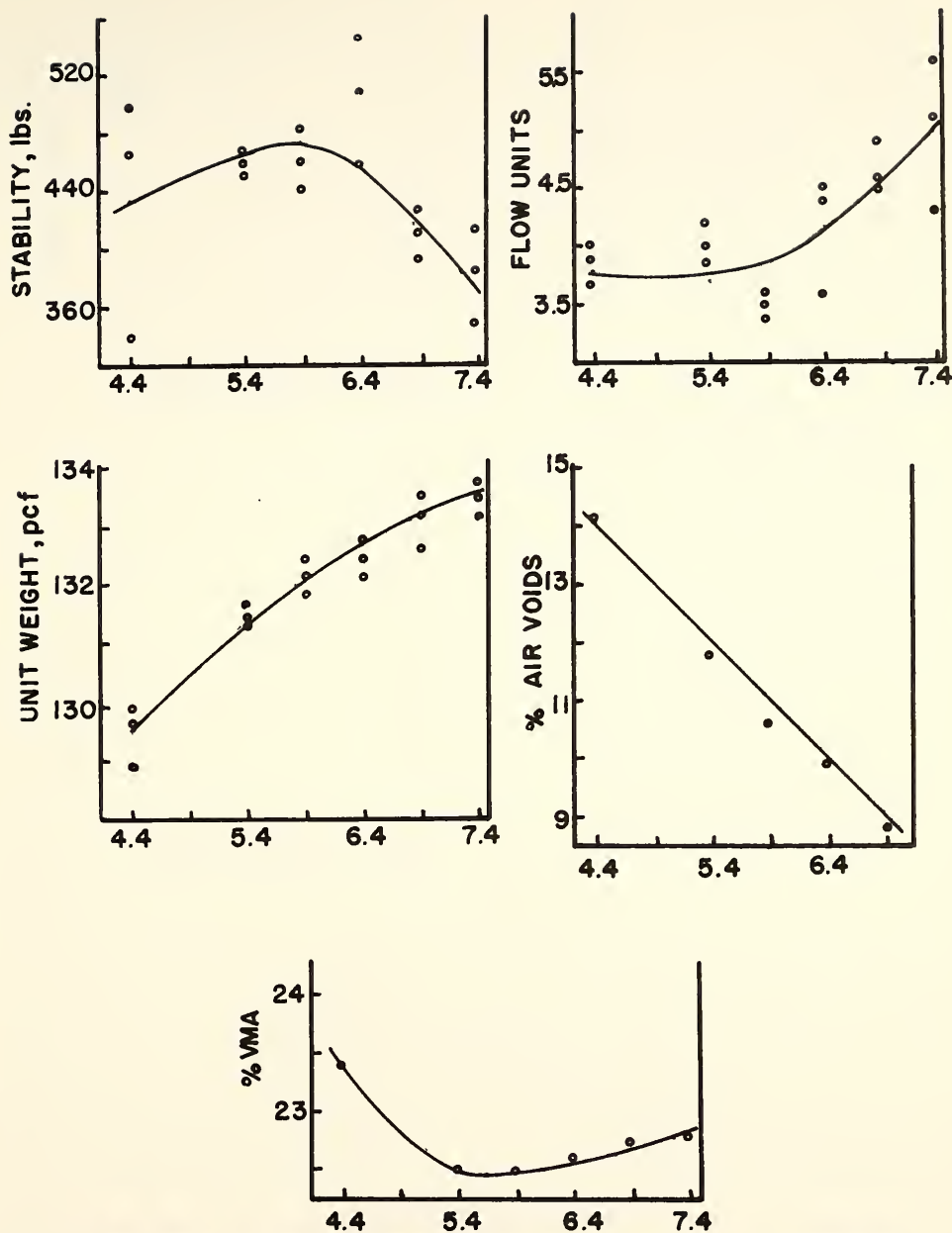


**FIGURE 28 MARSHALL DESIGN CRITERIA VS. ASPHALT CONTENT
SAND- 0% ASH**

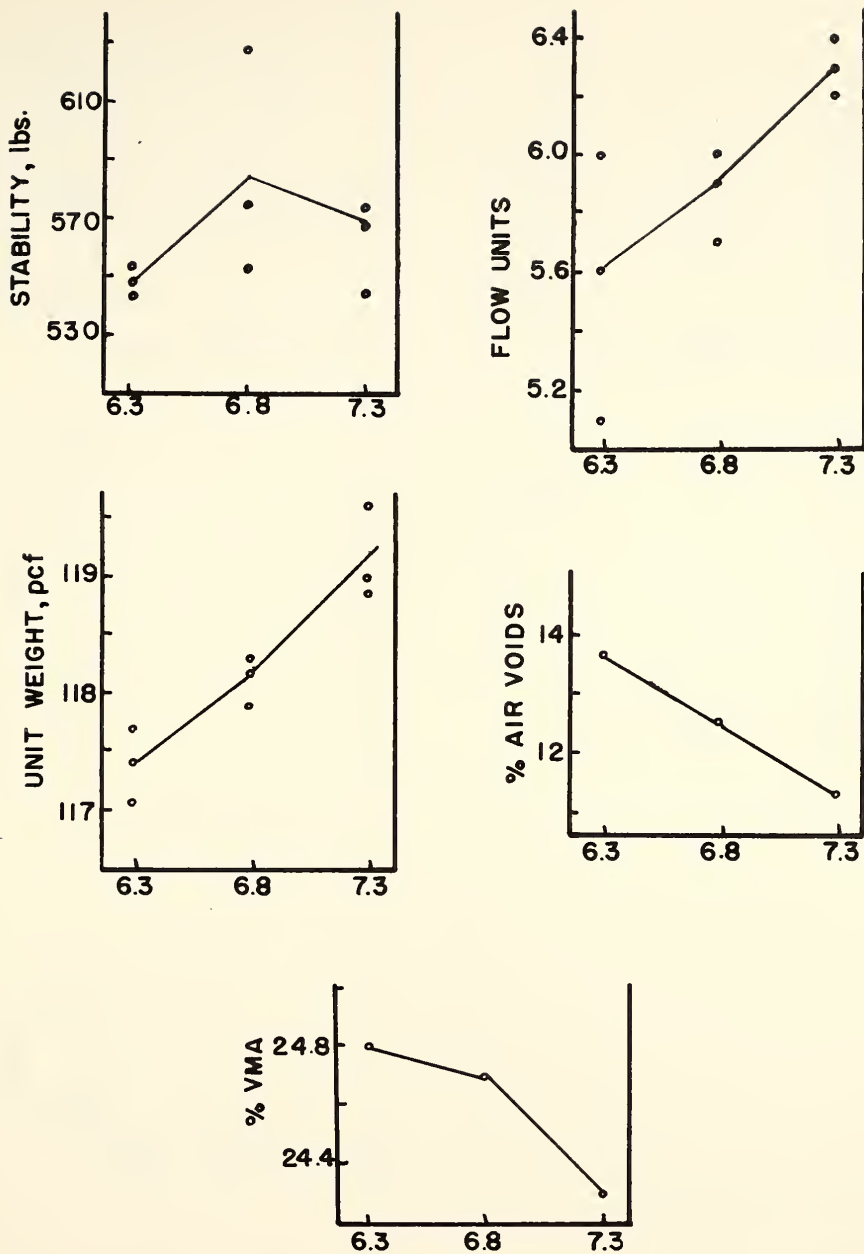


FIGURE 29 MARSHALL DESIGN CRITERIA vs. % ASPHALT
SAND - 25% PURDUE

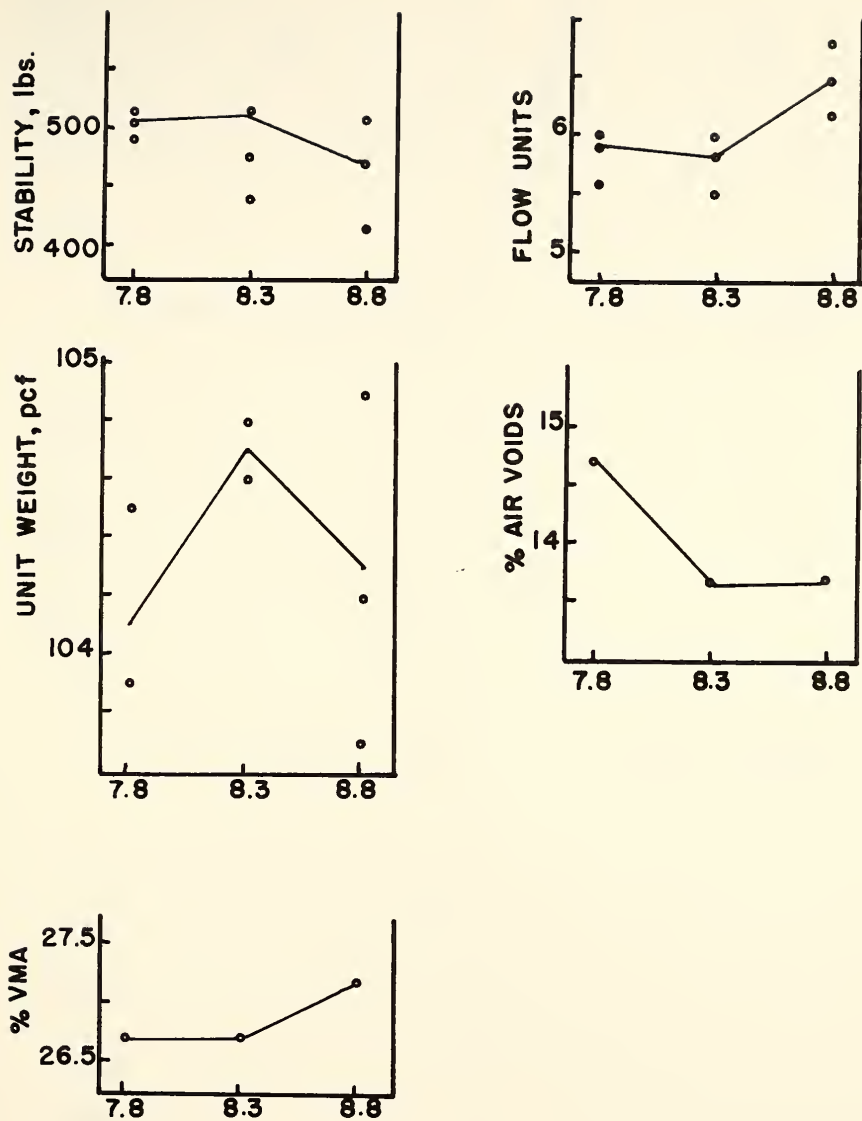


**FIGURE 30 MARSHALL DESIGN CRITERIA vs. % ASPHALT
SAND - 50% PURDUE**

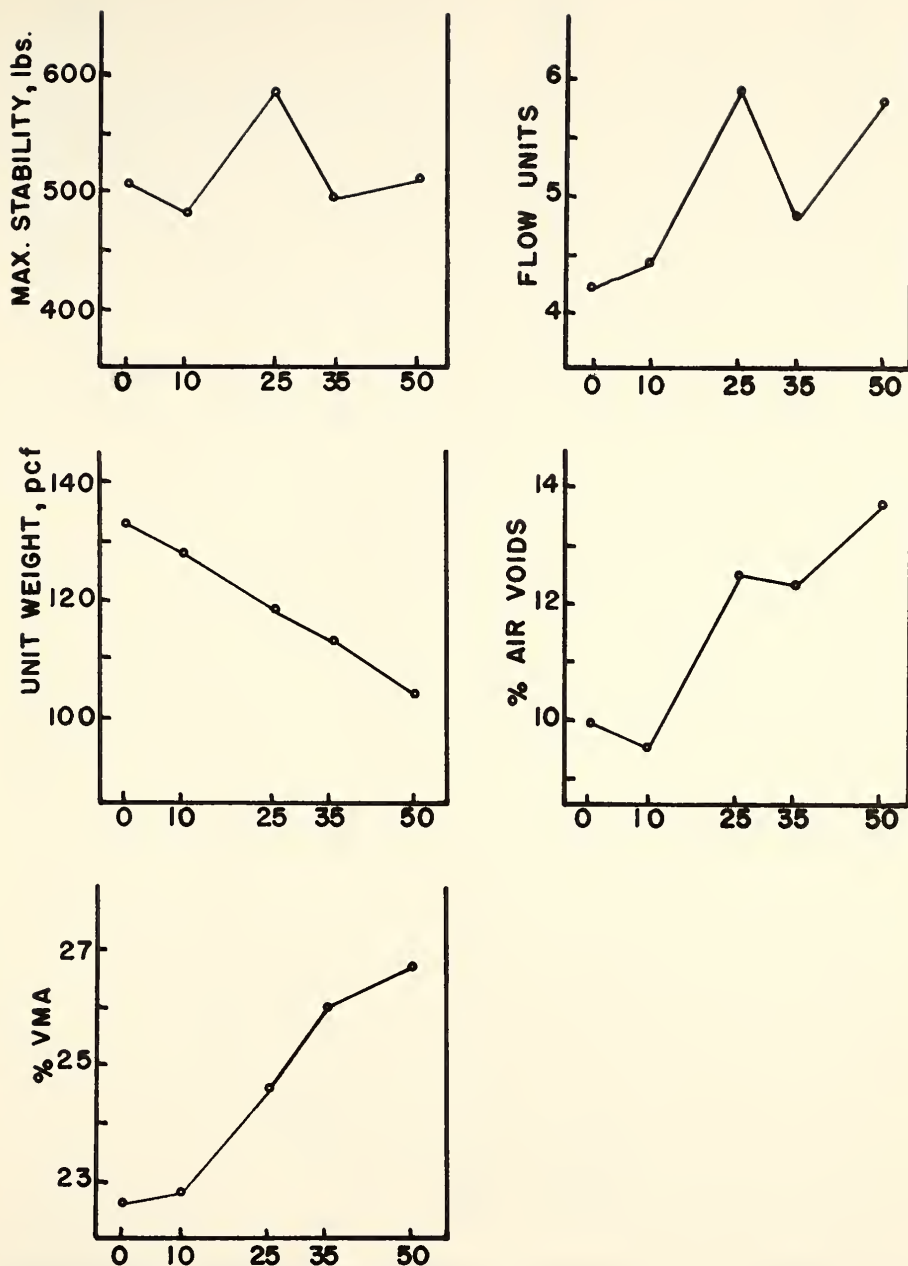


FIGURE 31 MARSHALL DESIGN CRITERIA vs. % ASH AT OPTIMUM % ASPHALT FOR SAND-PURDUE

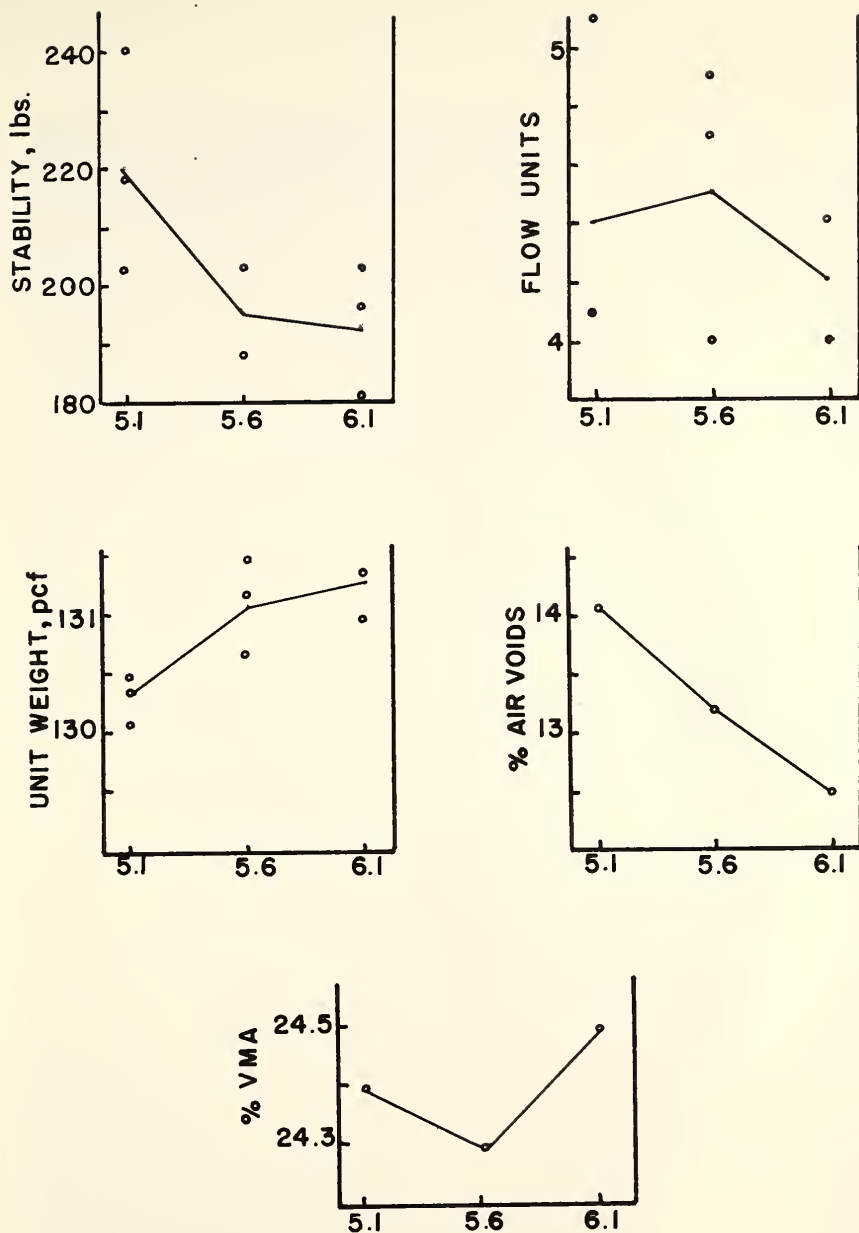


FIGURE 32 MARSHALL DESIGN CRITERIA vs. % ASPHALT SAND-25% PSI ASH



FIGURE 33 MARSHALL STABILITY vs. % ASPHALT vs. % ASH FOR LIMESTONE AND PURDUE ASH MIXTURES

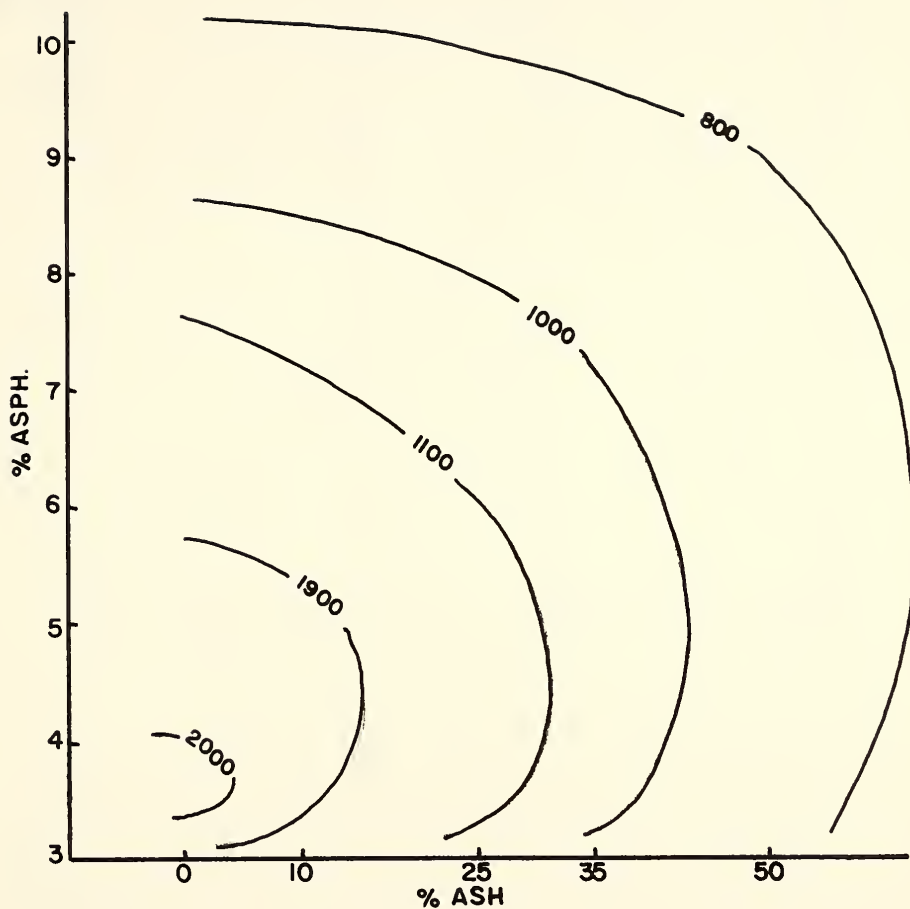


**FIGURE 34 % ASPHALT vs. % ASH — MARSHALL
STABILITY CONTOURS IN lbs.
LIMESTONE - PURDUE ASH**

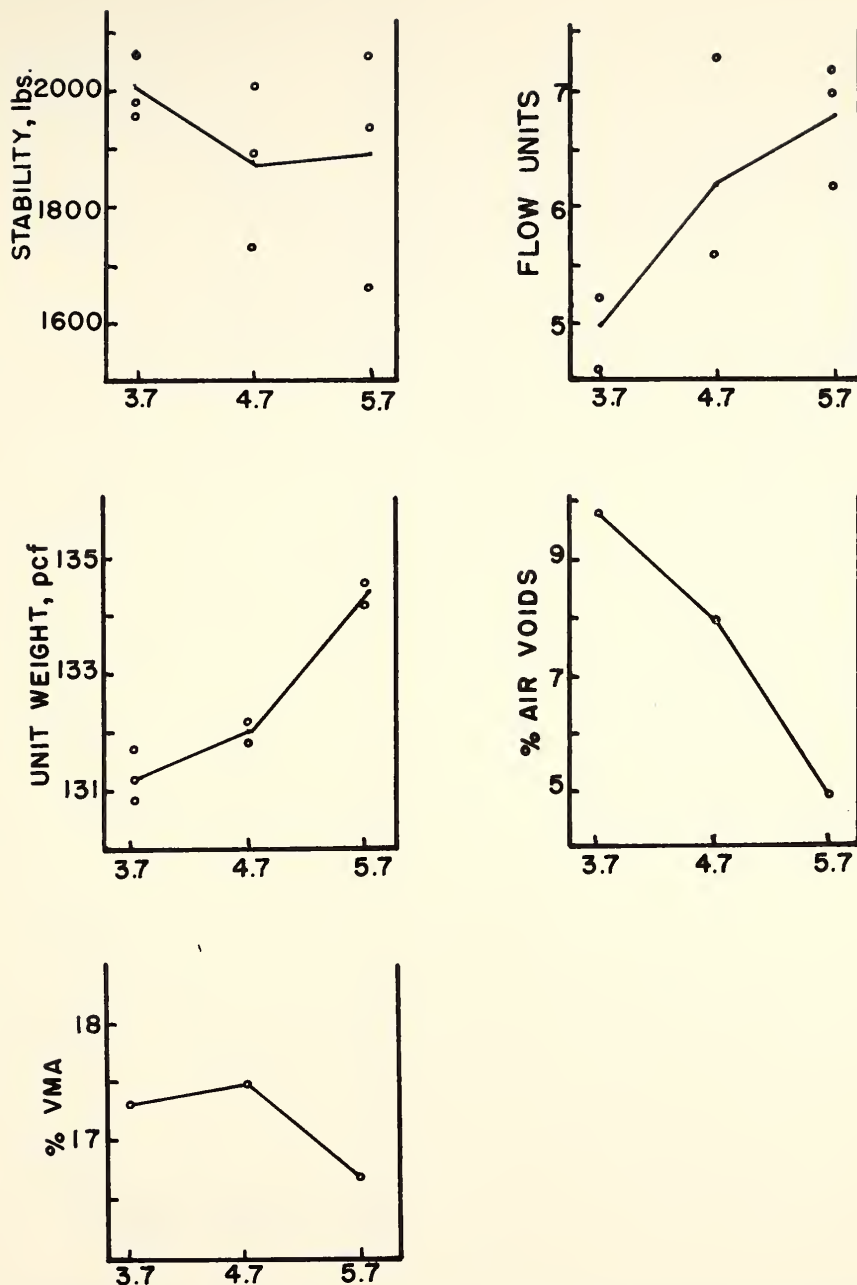


FIGURE 35 MARSHALL DESIGN CRITERIA vs. % ASPHALT
LIMESTONE - 0% ASH

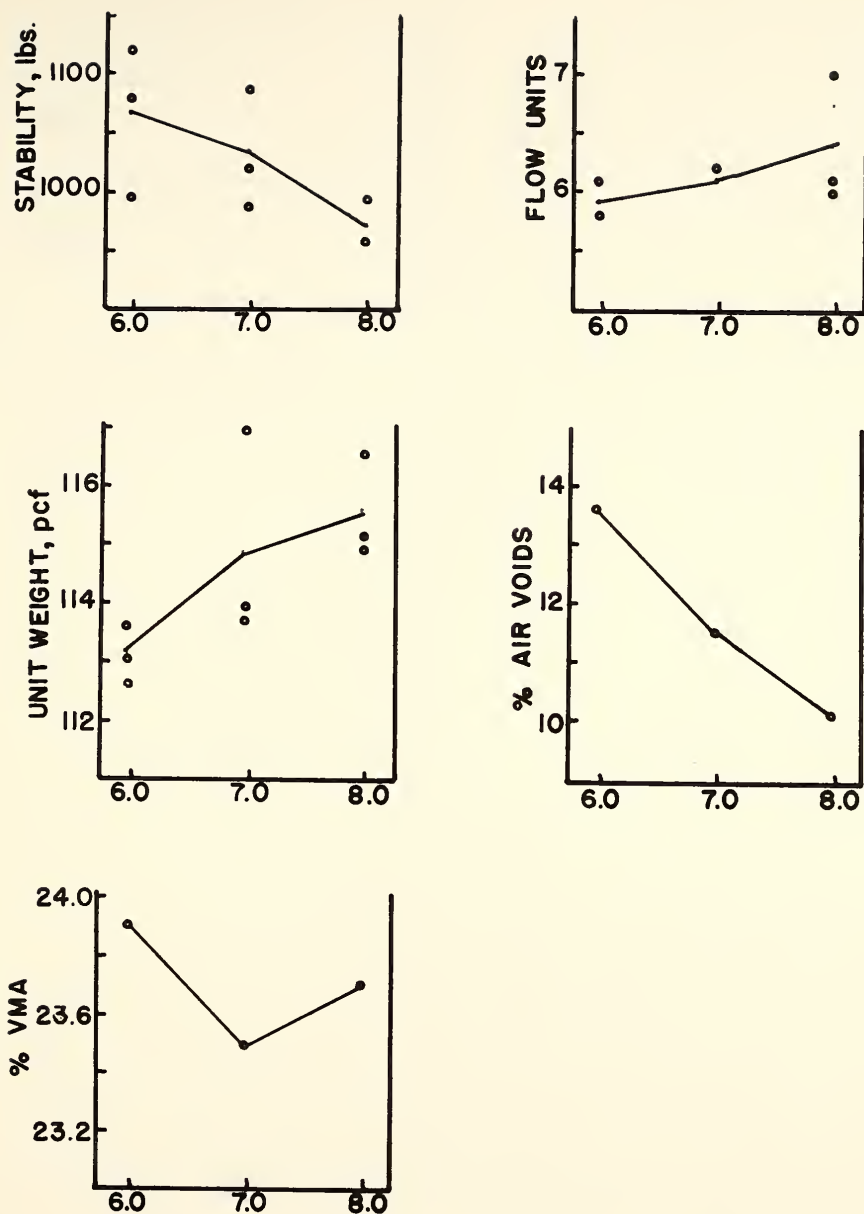


**FIGURE 36 MARSHALL DESIGN CRITERIA vs. % ASPHALT
LIMESTONE-25% PURDUE ASH**

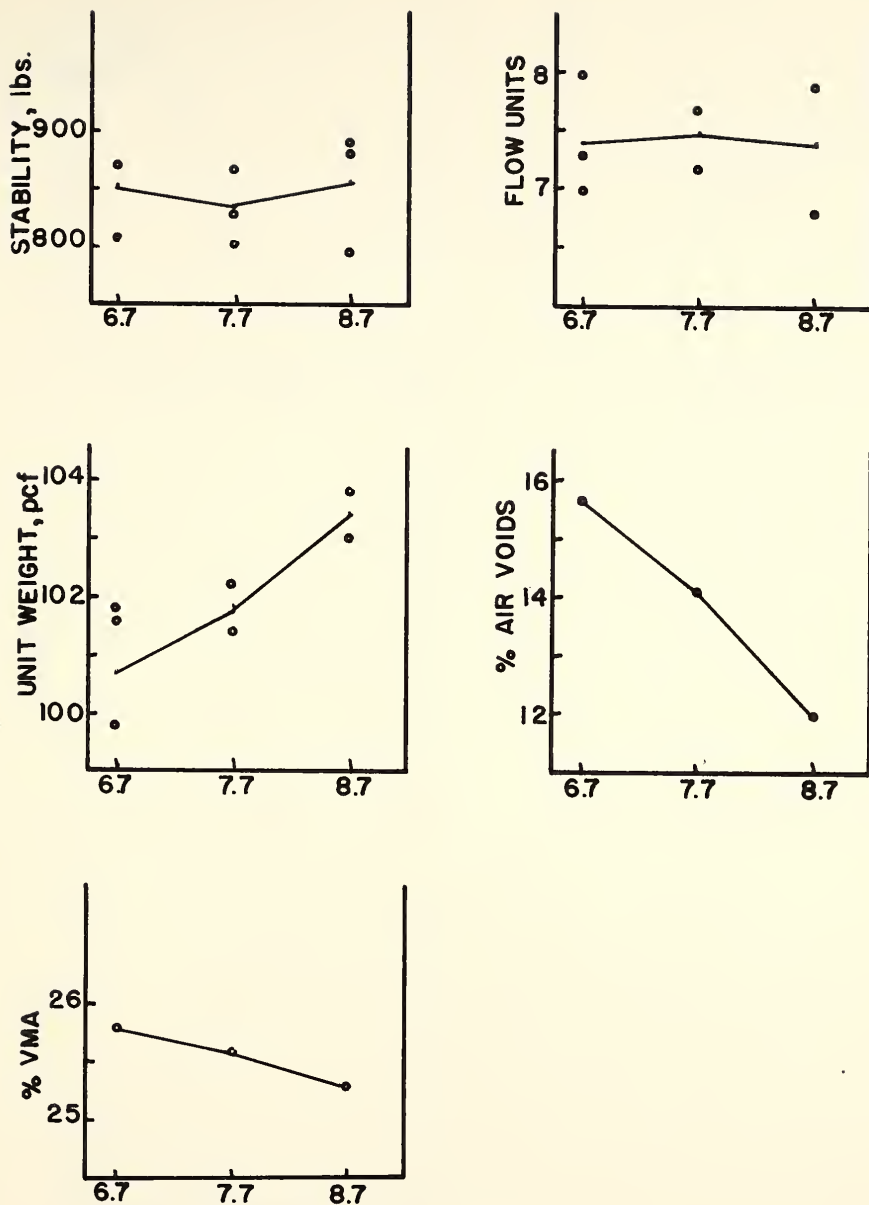


**FIGURE 37 MARSHALL DESIGN CRITERIA vs. % ASPHALT
LIMESTONE - 50% PURDUE ASH**

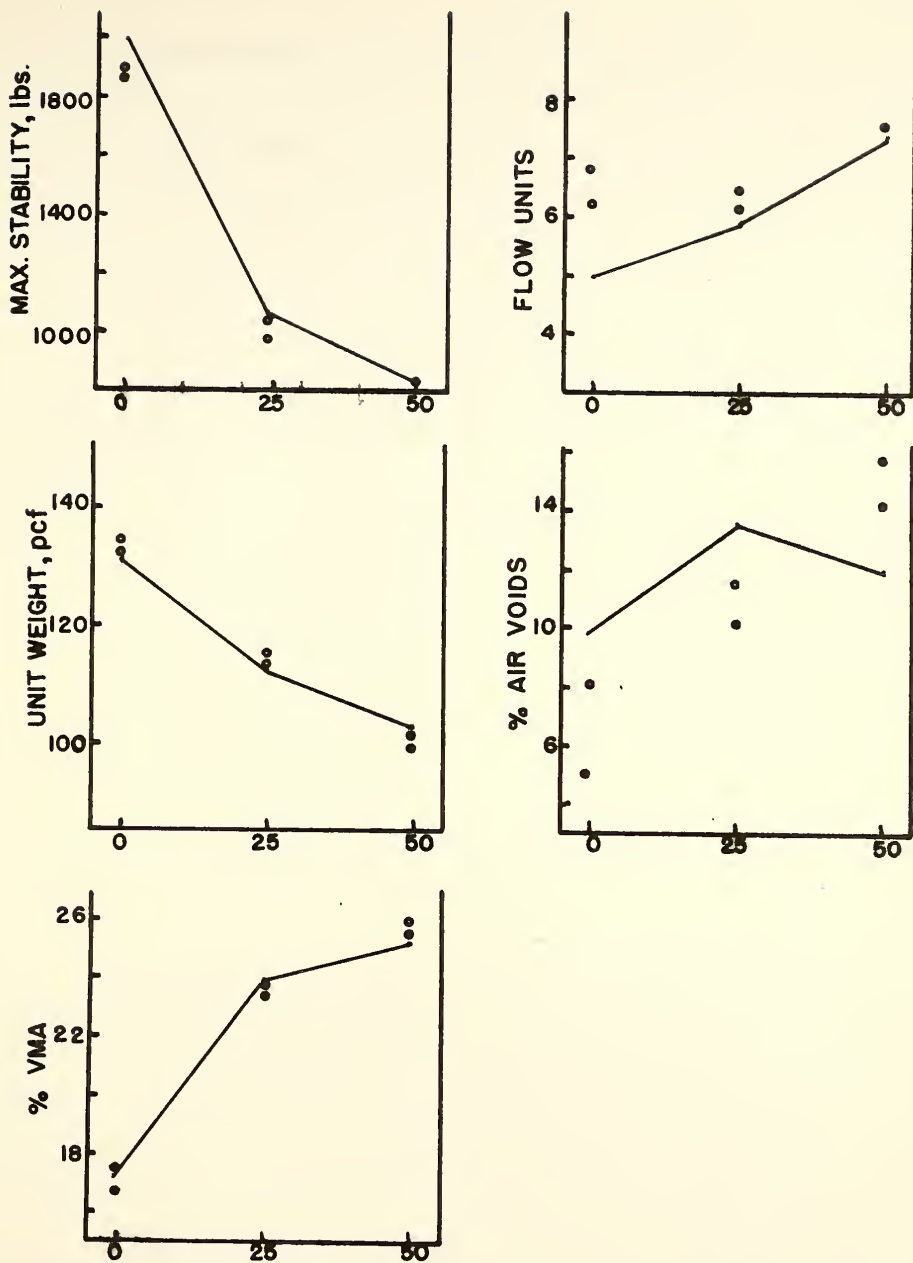


FIGURE 38 MARSHALL DESIGN CRITERIA vs. % ASH AT OPTIMUM % ASPHALT LIMESTONE-PURDUE

Limestone and Public Service Indiana (PSI) Ash. The PSI ash had the same effect upon the stability of the limestone as the PURDUE ash did, only to a greater degree.

A 2000 lb stability at 0% ash content is decreased to 500 lbs with 50% ash content.

Flow values remain constant.

The effect of varying PSI ash contents and asphalt content upon the Marshall design values are shown in Figure 39.

Water Sensitivity Test

The four subsections of this test include:

- a. Density and Voids Analysis
- b. Group II Marshall Stabilities and Flow
- c. Retained Stability, %
- d. Water Absorption, %

a. Density-Voids Analysis. Refer to Table 4 for specific data described below.

Sand and PURDUE Ash. The trend occurring in these tests is an inverse relationship involving the density and air voids of the mixtures. As the amount of ash contained within the specimen is increased, the air voids increase in proportion, causing the density to be lowered.

Sand and Public Service Indiana (PSI) Ash. The same trend is evident here but is less dramatic than the PURDUE ash with sand mixtures.

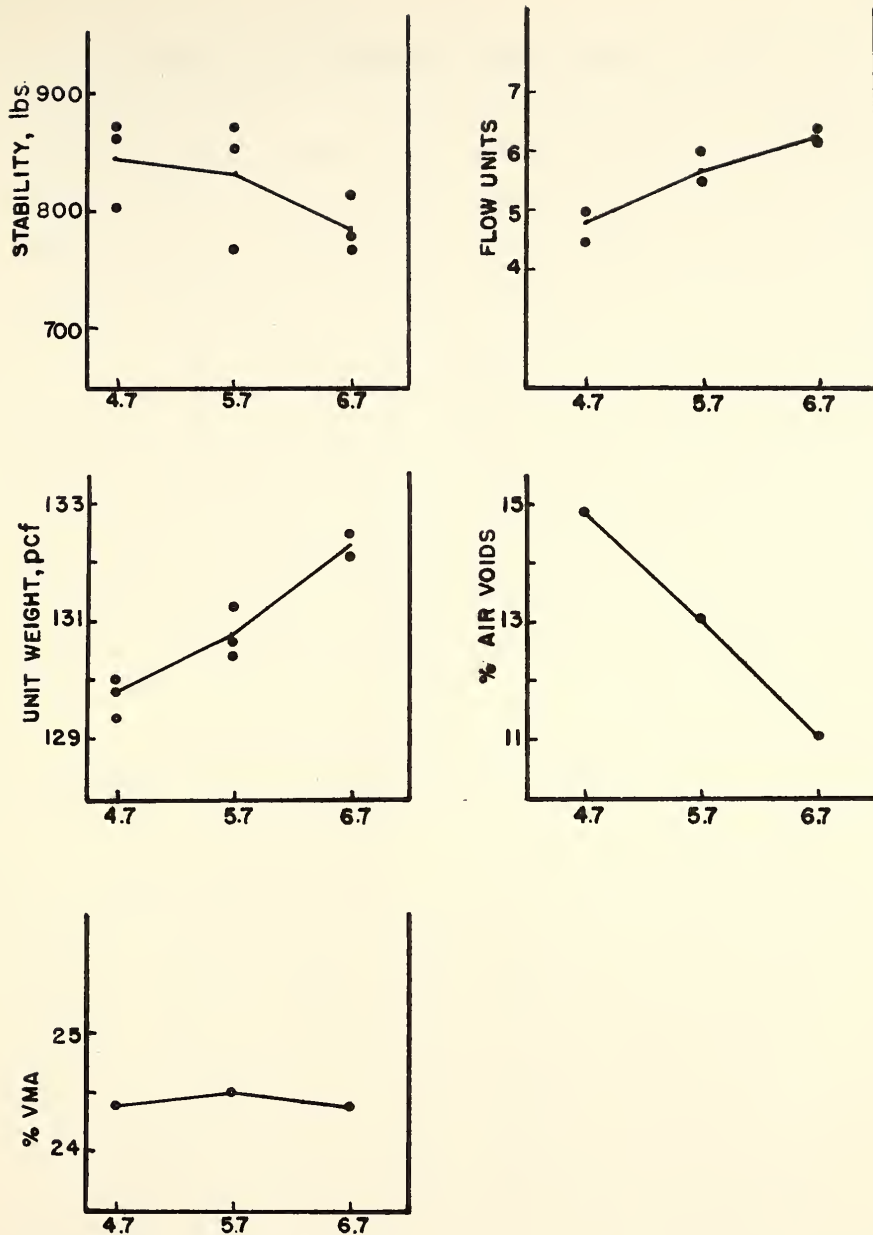


**FIGURE 39 MARSHALL DESIGN CRITERIA vs. % ASPHALT
LIMESTONE-25% PSI ASH**

Limestone and PURDUE and Public Service Indiana Ash.

These combinations reveal the same trends already discussed in the above two cases. The limestone-PURDUE combinations show a large decrease in density-increased in air voids as ash content is increased. The limestone-PSI mixtures show this same trend but to a lesser degree.

b. Group II Marshall Stability and Flow. The results of this test are used with the Group I results to obtain a quotient termed "Retained Stability."

In every case the Group II stabilities were lower than the Group I. Concurrently, the Group II flow values were always higher than the Group I. The reader is directed to Table 4 for the desired details.

c. Retained Stability, %. See Table 4 for a direct comparison of results described below.

Sand and PURDUE Ash. The sand was able to maintain 53% of its stability with an ash content of 0%. As more ash was added, the stability retention of the mix was greatly enhanced. At ash contents of 25% and 50% the stability retained was 91.5% and 99.9% respectively.

Sand and Public Service Indiana (PSI) Ash. The PSI ash enabled the sand to retain 93% of its dry stability. The sand retained only 53% of its stability without the aid of the ash.

Limestone and PURDUE Ash. Very good stability retention was exhibited when these two materials were combined. Values of over 90% were consistent at all ash contents.

Limestone and Public Service Indiana (PSI) Ash. The limestone had very good stability retention, 92%, at 0% ash content. This excellent retention was not affected by the PSI ash until the 50% ash replacement quantity was reached. Retention then fell to 85%.

d. Water Absorption, %. Air voids increased as ash contents increased. This resulted in proportional water absorption for all aggregate-ash combinations. Table 4 should be referred to for specific data.

Hveem Stability

ASTM D 1560: Mixtures were selected for a determination of Hveem Stability and Cohesion on the basis of their performance in the Marshall Test. The sand and PURDUE specimens were subjected to a more comprehensive analysis than the other mixtures. Reference to Table 4 will be helpful while reviewing these results.

Sand and PURDUE Ash. The overall trend in stability for these specimens does not increase as the ash is introduced into the mixture. It must be noted that, in general, the maximum stability values occur at higher asphalt contents as the ash content of the specimen is increased.

This fact makes direct comparison of stabilities of specimens with equal asphalt contents but varying ash contents impractical. See Table 4 for a complete summary of specific data.

Sand and Public Service Indiana (PSI) Ash. The decreasing stability trend with increasing amounts of ash was also observed with this series, as 12% of the stability is lost at an ash content of 25%. Values range from 25 to 22 at 0% and 25% ash, respectively.

Limestone and PURDUE Ash. A decrease in stability with an increase in ash content was again noted in this particular aggregate-ash combination. A 30% loss in stability from 0% to 50% ash was observed. Hveem Stabilities ranged from 36 at 0% ash to 25.5 at 50% ash.

Limestone and Public Service Indiana (PSI) Ash. The trend of loss in stability with an increase in ash content was also observed for this combination. More than a 40% loss in strength occurs at a 50% ash content. Values range from 36 to 20.5 at 0% and 50% ash content respectively.

The Hveem Stability Value is calculated as follows:

$$\text{Stabilometer Value, } S = \frac{22.2}{\frac{P_h D_2}{P_v - P_h} + 0.222}$$

S = relative stability

D_2 = displacement on specimen

P_v = vertical pressure at 400 psi

P_h = horizontal pressure corresponding to $P_v = 400$ psi

Hveem Cohesion

ASTM D 1560: The general trend in these data reflected the results obtained from the stability test. As ash contents rose, cohesion decreased to a point, then levelled off. The sand and PURDUE combinations show no particular trend as the cohesion values remain approximately constant.

A review of Table 4 summarizes these results.

The Cohesimeter Value is calculated as follows:

$$C = \frac{L}{W(0.20H + 0.044H^2)}$$

where:

C = Cohesimeter Value (grams/inch width, corrected to 3 inch specimen height)

L = Weight of shot, grams

W = Diameter of specimen, inches

H = Height of specimen, inches

Density-Voids Analysis, Hveem Tests

ASTM D 1560: The trend in density-voids values for the Hveem tests parallel those of the Marshall since the same materials and compaction techniques were used in both procedures.

Skid Resistance

ASTM C 303: All tests for skid resistance were performed on aggregate-asphalt mixtures reflecting maximum Marshall Stability values. No previous abrasion had been administered to the specimens prior to actual testing. Water temperature at the time of the test was 73°F. Refer to Table 4 for a direct comparison of data.

Sand and PURDUE Ash. An obvious upward trend in skid resistance was demonstrated by these materials as the ash content increased. The skid resistance at 0% ash averaged 66 while at 50% ash the average skid resistance was 80.

Sand and Public Service Indiana (PSI) Ash. The trend exhibited here was not equal to that of the sand with PURDUE ash. The average skid resistance for an ash content of 25% was virtually equal to the average for 0% ash. These values were 66 for 0% and 67 for 25% ash, respectively.

Limestone and PURDUE Ash. The skid resistance increased proportionally with the ash content. At 0% ash the skid resistance averaged 72. This increased quickly to an average of 88 at 50% ash.

Limestone and Public Service Indiana (PSI) Ash. Again, the trend exhibited by the PURDUE ash was not shared by the PSI ash. The skid resistance at 0% ash averaged 72 while at 50% ash an increase to only 75 was demonstrated.

Degradation Analysis

Sand and PURDUE Ash. No clear trend in the data appears with these two materials. Values of the difference in Aggregate Gradation Moduli ($\Delta\bar{\Sigma A}$) appear to remain constant with minor fluctuations. See Table 4 for specific examples of data. The complete degradation analysis for the mixtures is presented in Table 5.

Sand and Public Service Indiana (PSI) Ash. The $\Delta\bar{\Sigma A}$ developed for the mixtures of sand and PSI had lower absolute values than corresponding sand and PURDUE mixtures. See Tables 4 and 5. This is not surprising since the PSI ash degraded less than the PURDUE in the ash degradation analysis (see Table 2).

Limestone and PURDUE Ash. A trend seems to be exhibited by these materials. The absolute $\Delta\bar{\Sigma A}$ values seem to increase slightly as ash is introduced to the mixture. This trend is easier to establish than with the previous mixtures, but is still not clearly evident.

Limestone and Public Service Indiana (PSI) Ash. The $\Delta\Sigma\bar{A}$ demonstrated here had lower absolute values than for corresponding mixes of limestone and PURDUE ash. Again, this lower trend in the limestone, PSI $\Delta\Sigma\bar{A}$ values seems to be indicative of lower $\Delta\Sigma\bar{A}$ values of PSI ash over PURDUE ash in the ash degradation analysis, see Table 2.

Table 5
Degradation Analysis Summary
Aggregate and Ash Mixtures

Sand Specimen	$\Delta\Sigma\bar{A}$ %	Limestone Specimen	$\Delta\Sigma\bar{A}$ %
7.4S0A1	-2.5	4.7L0A1, 2	-4.82
7.4S0A2, 3	+2.5	4.7L0A3	-6.75
		5.7L0A1, 2	-4.15
7.4S10A1, 2	-2.93		
7.4S10A3	-3.91	6.0L25A3	-7.11
6.3S25A1, 2	-3.00	6.7L50A1, 2	-6.20
6.3S25A3	-2.71	8.7L50A1, 2	-6.96
6.8S25A1, 2	-3.35	8.7L50A3	-7.80
6.8S25A3	-3.28		
7.3S25A1, 2	-3.18	4.7L25A1, 2P	-2.34
7.3S25A3	-3.88	4.7L25A 3P	-5.83
7.5S35A1, 3	-3.54		
		4.7L50A1, 2P	-4.42
7.8S50A1, 2	-3.13	4.7L50A 3P	-5.32
7.8S50A3	-4.80		
5.1S25A1, 2P	-2.00		
5.1S25A3P	-2.10		
6.1S25A1, 2P	-3.39		

CHAPTER VI DISCUSSION OF RESULTS

The format for this chapter is identical to that of Chapter V. A discussion of the ash characterization will precede the discussion of the mix design portion.

Ash Characterization

Unit Weight

ASTM C 29: The unit weights obtained for the ash did not directly reflect the value of the specific gravity of the material. The unit weight was dependent upon the specific gravity and the gradation involved. A densely graded, high specific gravity material gave rise to the highest unit weights.

Florida Bearing Test

Ind 201-72: The data obtained from this test were not as significant in the prediction of stability performance for the bituminous concrete mixtures of ash and mineral aggregate as at first believed. The test gave an excellent basis for characterizing the ash products, however. Reference to Table 1 of Chapter V indicates that three of the six ash products tested have Florida Bearing Values (FBV) less than 100 and three have values exceeding 100.

The recorded values of plus 100 are indicative of materials which showed no tendency to fail under the imposed load. A value of 100 for the Florida Bearing Test indicates an inherently strong material. A value of 30 is considered quite satisfactory for aggregates used in surface course mixtures (41) in Indiana.

Two characteristic ash classes began to develop as the Florida Bearing Test results were completed. The materials in Class I had FBV's below 100 and consisted of the BREED, PSI and NIPSCO materials. Class II consisted of the STOUT, ALCOA and PURDUE ash products with FBV in excess of 100.

It should be noted that the two ash classes were not composed of wet bottom and dry bottom ash respectively. Wet bottom ash was present in both groups. The class distinction seemed to be independent of the boiler type used. As other tests were run on the materials it became more apparent that two distinct classes of material existed.

Centrifuge Kerosene Equivalent and Oil Ratio

ASTM D 1560: The results of this test further confirm the presence of the two ash classes.

The ash with the high FBV exhibited high CKE values. See Table 1 for a comparison. The ALCOA, STOUT and PURDUE CKE values were 4.6, 5.1 and 10.4 respectively. These are all extremely high values, indicating a very high absorptive capacity.

The ash with the relatively low FBV however, indicated a lower potential for absorption with CKE values in the 1.0 to 1.4 range.

The open, vesicular, surface texture displayed by the ashes of Class II is apparently responsible for their high FBV and CKE values. The smooth, glassy characteristics of the Class I materials give rise to lower FBV and CKE results.

The CKE test proved to be very useful in determining the design asphalt content of the mixtures. The dual role it played in ash characterization and mix design made it that much more beneficial.

Specific Gravity

ASTM C 127, C 128: This test gave further evidence that two characteristic ash classes existed. Refer to Table 1 of Chapter V for specific values. Class I ash had high specific gravity values. These ranged from 2.56 to 2.79. The Class II materials displayed specific gravity values ranging from 1.80 to 2.35. Again, the reason seems to be due to the glassy and dense nature of the Class I materials. The manner in which these materials have been handled seems to prevent large quantities of voids from forming which results in the high material densities.

Categorization of the ash into classes on the basis of specific gravity alone would be a very cursory judgement if results such as those presented here were encountered. These results are useful only to distinguish between wet

and dry bottom ash. A large difference exists between the low, dry bottom values and the higher, wet bottom values. Refer to Table 1 for a complete review of specific gravity results.

Sieve Analysis

ASTM C 136: The characterization of the two ash classes is further substantiated with the results from this test as depicted in Figures 14 through 19. Two general gradations are present. These two gradations seem to be due to plant operations rather than to inherent ash properties. This test seems to characterize the type of ash handling operation present at the power plant.

The Class I ash had an essentially one-sized gradation. This could indicate a controlled crushing operation prior to slurry transport. The Class II ash had sieve analyses which indicated a range of sizes.

The Class I materials were stockpiled exclusively as bottom ash, while the Class II materials were stockpiled with the fly ash from the smokestacks. The Class II materials also have a greater potential for heterogeneity since wet and dry bottom ash are combined at one site, wet bottom ash is produced in dry bottom boilers at another site, and straight dry bottom ash is manufactured at the third facility. Comparing this variance of procedures with the relatively constant operations found among the Class I plants, it is not surprising that two types of gradation exist.

Degradation Analysis

The Aggregate Gradation Modulus ($\bar{A}$) as prescribed by Hudson and Waller (38), was the means used to classify the ash with respect to degradation characteristics. See Appendix A for an example of the calculations. This method was chosen because the ash being evaluated had varying gradation characteristics. The determination of the factors $\bar{A}$ and corresponding A_i constants allow direct comparisons between various samples of differing gradations to be made. The two ash classes described in the previous ash tests are verified in Tables 1 and 2. Class I ash had significantly lower ($\bar{A}$) values than Class II ash. The direct comparisons may be seen in Tables 1 and 2. This fact seems to be related to the inherent differences found between the two ash categories. The vesicular and friable nature of the Class II ash would seem to be the reason for this material's relatively lower $\Delta\Sigma\bar{A}$ values. The glassy characteristics of the Class I ash gave rise to the higher $\Delta\Sigma\bar{A}$ results.

Mixture Design

Florida Bearing Test

Ind 201-72: Various combinations of mineral aggregate and bottom ash were evaluated and gave expected results.

All variations of ash and mineral aggregate to be used in the study were evaluated. These combinations included: Sand - PURDUE; Sand - PSI; Limestone - PURDUE; and Limestone - PSI, and the results are presented in Figures 21 through 24.

In addition, combinations of the sand with the remaining four ash types were evaluated. The results obtained in this subset of the experiment are presented in Figure 20.

It is easy to predict the general outcome of mixing two of these materials together by observing the individual FBV. If a material with a high FBV is mixed in gradually increasing amounts with a material of a low FBV, the net result will be an intermediate FBV for the total mixture.

This method seems to be successful only in predicting FBV, however. The limited number of tests performed in this study suggest that little correlation is possible between Florida Bearing results and Marshall or Hveem stabilities. More Hveem Stability tests are required to substantiate this hypothesis, however.

Marshall Stability and Flow

ASTM D 1559

Sand and PURDUE Ash. Highly repeatable results were difficult to obtain with this test since a large margin is available for experimental error. This is one reason why

the data collected from this test should be viewed in a rather cursory manner, and should be used to only indicate trends in the data.

The trend for the sand and increasing amounts of PURDUE ash is difficult to ascertain. A slight upward stability trend exists while flow values are generally constant. See Figures 26 through 31 and Table 4.

The low flow values seem to be linked to the low stability values. The specimens fail at low stability values, thus the sample has very little time to strain before failure has occurred. This is not a general phenomenon, but limited to these mixes only.

Sand and Public Service Indiana (PSI) Ash. A definite trend was established with these two materials. The marked effect of the PSI ash upon the Marshall stabilities of the sand-PSI ash combinations may be seen in Table 4 and Figure 32. The glassy appearance of the ash might lead one to expect a lowering of Marshall stabilities in this case. The two "smooth" textured aggregates in combination allow for a marked reduction in stability for this particular mixture.

The flow values, which remained fairly constant, are still low, and can probably be linked to very low failure stresses as discussed previously.

Limestone and PURDUE Ash. The very high stability of the limestone mixtures alone is an indication that addition of other solid materials might reduce the already excellent stability results. The addition of the PURDUE ash had a detrimental effect on the limestone's stability traits (see Table 4 and Figures 33 through 38), but considering the amount of stability the stone mix had initially, these effects are not necessarily damaging. The lowest stability recorded for 50% PURDUE ash and limestone was 830 pounds, over 300 pounds greater than the highest stability recorded for sand and PURDUE ash. This 830 pound value is also only 170 pounds below the minimum 1000 pound recommendation prescribed by the Asphalt Institute for surface mixes (38).

Flow values rose from 5.0 (0.05 inches) to 7.5 (0.075 inches). The minimum flow value suggested by the Asphalt Institute is 8.0 (0.08 inches), see Table 4 and Reference (38).

Limestone and Public Service Indiana (PSI) Ash. The effect the PSI ash had upon stability was emphasized here as it was with the sand. This detrimental effect upon stability is not that damaging, however, for this limestone mix. See Table 4 and Figure 39 for examples. The maximum 2000 pound stability value obtained with 0% ash was lowered to 460 pounds when 50% PSI ash was contained in the mixture. This low 460 lb value is within the range of the stability

values associated with the sand-PSI ash mixtures. Therefore, although the PSI ash seems to be a deterrent to this limestone paving mixture's performance, it should not be discounted until all other data have been collected. See Table 4 for a comparison of the sand and limestone performances.

The flow values remained constant as the stability dropped. This seems to again be attributed to the low stress occurring at failure for these particular mixtures.

In both cases where PURDUE ash was included in a mixture the asphalt content necessary to maintain maximum stability had to be raised in proportion to the ash quantity, see Figures 27 and 34.

Water Sensitivity Test

a. Density-Voids Analysis. All voids were calculated based upon bulk specific gravity data. The values tabulated, therefore, will be lower than the absolute voids contained. This method was used because a general trend in voids data was of interest, not absolute values.

Sand and PURDUE Ash. The extremely porous nature of the PURDUE ash, as evidenced by CKE values greater than 10.0, allows an inverse relationship to exist between density and air voids as ash and asphalt quantities are

increased. Table 4 and Figures 28 through 31 depict these results. This high degree of porosity could also be the reason the density values do not reach a maximum point when stability values do, in the case of constant ash quantities. The asphalt seems to be incapable of filling all of the voids and thus a weakening of the structure occurs before the void volumes have been filled. This allows density values to continue increasing after stability values have begun to decline.

Sand and Public Service Indiana (PSI) Ash. Density values still do not reach a maximum point for these materials as asphalt content is increased (see Table 4 and Figure 32).

The high specific gravity, 2.70, of the PSI ash, and relatively low CKE value, 1.0, allows for much less a decrease in density as ash quantities are raised.

Limestone and PURDUE Ash. The results obtained here are of the same trend associated with the sand and PURDUE ash. An overall density decrease as ash was added, together with higher asphalt contents necessary to maintain the maximum stability values, allow for direct comparison with the sand and PURDUE results. Table 4 and Figures 35 to 38 depict these results.

Limestone and Public Service Indiana (PSI) Ash. The results obtained with these mixes demonstrate the same

trend that occurred with the sand and PSI mixtures. The density values decrease but little as ash is added. This fact strongly suggests that the air voids are not being filled with asphalt, since the specific gravity of the ash is greater than that of the limestone. See Table 4 and Figure 39.

b. Marshall Stability and Flow, Group II. The Group II, or soaked, Marshall Stabilities were lower than the Group I Marshall Stabilities for every case tested, see Table 4. This is not surprising considering the severity of the test. The relative amounts of stability loss are a function of the saturated mixture's capacity to withstand the forces of heated water. This discussion will be handled in more detail in the following section entitled "Retained Stability."

c. Retained Stability, %

Sand and PURDUE Ash. The results of this test appear to indicate that when increasing amounts of ash with Class II characteristics are incorporated in the bituminous mixture, the specimens are able to retain a higher percentage of their dry stability when subjected to the soaked condition than the same mixture without the aid of the ash. See Table 4 for a direct comparison of Group I and Group II results.

Sand and Public Service Indiana (PSI) Ash. The retention of Group I Marshall Stability values with increasing quantities of ash continues with this series of materials (see Table 4). The stability retained (73%) with 25% PSI is greater than that of the sand mixtures alone (53%).

Limestone and PURDUE Ash. The PURDUE material did not effect the limestone significantly with respect to retention of stability in the soaked condition. The limestone exhibits 92.0% stability retention with 0% ash. At a 50% ash content the retention was 95.5% (see Table 4). These results, combined with the increase in retention the PURDUE ash gave to the sand, make this a valuable material where resistance to deterioration due to water are concerned.

Limestone and Public Service Indiana (PSI) Ash. The favorable results the PSI ash displays with the sand are not evident with the limestone. The high resistance the limestone exhibits to loss of stability under the action of water is lowered slightly by the PSI ash. At 25% ash content the stability retention seems to increase (see Table 4), but by 50% ash content the retention decreases to 85%. This small amount of variation is not significant when considering the inherent potential for inaccuracy within the test itself. See Table 4 for a direct comparison of results.

d. Water Absorption, %. The direct comparison of the water absorption with the quantity of air voids contained within each specimen led to a relationship which should be expected.

The specimens containing PURDUE ash have water absorption values which increased at a rate faster than the corresponding air void content (see Table 4). This result leads one to believe that the PURDUE material possesses a greater quantity of permeable voids than impermeable voids.

The specimens containing PSI ash have water absorption values that rise in proportion to their respective air void content. This might indicate that a more equal number of permeable and impermeable voids exist within the PSI ash framework (see Table 4).

Hveem Stability

ASTM D 1560: The lack of an increase in Hveem Stability exhibited by all of the mixtures as ash contents were increased was unexpected. Added investigations were performed utilizing the sand and PURDUE mixtures to help qualify this finding.

It was thought that the PURDUE ash would allow the original stability at 0% ash content to at least be maintained rather than to decrease. This decrease observed for the sand mixtures does not appear to be particularly significant, however.

The decrease in stabilities for the Hveem procedure parallels the results obtained in the Marshall test. No correlation between Marshall and Hveem results was attempted.

It should be noted that for the maximum stability to be maintained at varying PURDUE ash contents the asphalt content had to be increased accordingly. Table 4 displays these results.

Hveem Cohesion

ASTM D 1560: The trend involving strength reduction as ash is added to the mixture is reinforced with the results of this test (see Table 4). Comparing the Hveem Stability results with the results from this test one can observe the greater effect of reduction of cohesion with respect to the PSI ash. The PSI material consistently has a greater effect upon mixture performance than the PURDUE material. The results obtained from this test are limited to few data, and thus a general trend cannot be predicted.

Density Voids Analysis, Hveem Tests

ASTM D 1560: The compaction techniques and materials used for the Hveem tests were the same as used for the Marshall tests giving results that parallel the Marshall density-voids data (see Table 4).

Skid Resistance

ASTM E 303: The PURDUE bottom ash seems to offer a premium with respect to skid resistance. The PSI ash

offers only small improvement (see Table 4). The mixtures with PURDUE ash demonstrated marked increases in skid resistance from 0% to 50% ash, while the PSI material had insignificant influence upon the skid resistance of the mixtures.

The results obtained in this test reflect extremely high skid values for the samples tested. These high numbers, even for mixtures without ash, are indicative of a new pavement surface before the action of traffic has had the opportunity to wear off the rough surface texture.

The limestone mixtures indicate the highest initial skid resistance. It is suspected that these mixtures containing limestone will polish under the influence of traffic (40). The effect of the ash contained within these stone mixes with respect to polishing is unknown.

Degradation Analysis

Sand and PURDUE Ash. No specific trend seems to be present with these two materials. Only minor fluctuations in the data occur. No trend occurs even when asphalt content is varied within a particular test group.

The sand and 25% PURDUE group was evaluated for degradation at three asphalt contents (see Table 5). This evaluation was performed to determine whether asphalt content had a significant effect upon the mixture's degradation performance. A generalization cannot be made

based on only a single test, but these results seem to indicate that the asphalt has little effect upon degradation.

Sand and Public Service Indiana (PSI) Ash. A comparison between the corresponding sand, PURDUE and sand, PSI mixtures reveals lower degradation occurring in the sand and PSI specimens (see Table 5). In the ash characterization the PSI ash seemed to degrade less than the PURDUE ash (see Table 2). This lower degradation for the PSI ash appears to be the reason the mixtures of sand and PSI ash perform better than their corresponding sand and PURDUE mixtures.

Limestone and PURDUE Ash. The data for these materials indicate more of a trend than was found in the sand and PURDUE specimens. This trend seems to indicate higher degradation occurring within the aggregate framework as ash quantities increase. This trend is not highly pronounced, however, as $\Delta\Sigma\bar{A}$ values vary by only about 2.0 units on the average, see Table 5.

Limestone and Public Service Indiana (PSI) Ash. When a comparison is made between corresponding limestone, PURDUE and limestone, PSI mixtures a definite trend is found. The limestone and PSI mixes exhibit lower absolute $\Delta\Sigma\bar{A}$ values than their limestone and PURDUE counterparts. This seems to verify the lower absolute $\Delta\Sigma\bar{A}$ values obtained for the

PSI ash in the ash characterization study, see Table 2, Chapter V. It should be noted, however, that asphalt contents were not held constant in these tests and therefore generalities concerning degradation should not be made until further proof has been supplied.

The change in the $\Delta\Sigma\bar{A}$ values that occurred as a result of the compaction process was not studied sufficiently to validate this concept as a means of determining the degradability of bottom ashes prior to their incorporation into bituminous paving mixtures.

CHAPTER VII SUMMARY AND CONCLUSIONS

Ash Characterization

1. The six bottom ash materials used in this study were placed in two characteristic classes based upon physical tests performed on them.

2. The six ash materials as grouped in their respective classes are as follows:

Class I	Class II
BREED	ALCOA
NIPSCO	PURDUE
PSI	STOUT

Class I materials were glassy and durable while Class II ash was vesicular and friable.

Mixture Design

1. The Florida Bearing Test, when used as a pre-mix indicator of strength, had little success in predicting the trend in Hveem stabilities. However, limited Hveem testing was performed, therefore a final conclusion should not be attempted regarding the Florida Bearing Test's worth as a pre-mix stability indicator.

2. The addition of ash to the paving mixtures did not increase Marshall or Hveem stabilities.

3. Bituminous mixtures with ash demonstrated higher values for retained stability in the Water Sensitivity Test than mixtures without ash. Only one combination, the limestone and PSI ash, showed a slight decrease in retained stability.

4. Skid resistance of the mixtures was enhanced with the addition of ash. The PURDUE material had the greatest effect upon the mixtures, while the PSI ash showed insignificant improvement in skid resistance.

5. Greater degradation occurred in those mixtures containing PURDUE ash. This observation seemed to be due to the friable nature of this material.

CHAPTER VIII RECOMMENDATIONS FOR FURTHER RESEARCH

1. Verification of the results obtained from the ash characterization sequence of testing should be accomplished by including all ash sources in mixes to qualify the characterization tests as a valid screening device for determining pre-mix performance characteristics.

2. Additional Hveem testing should be conducted to determine whether the ash actually has a detrimental effect upon mix performance as evaluated by Hveem stability.

3. The gradation of the mixtures investigated could be varied to determine whether ash products might perform better with mixtures of one gradation than another.

4. The volume replacement of mineral aggregate in each sieve fraction could be varied instead of assigning a constant volume replacement. This procedure could take advantage of the physical characteristics of the mineral aggregate and bottom ash involved.

5. The use of two sources of bottom ash in one bituminous mixture could be investigated. Several types of ash could be mixed to obtain a final product containing the best characteristics of each ash.

6. The skid specimens tested in this study should be subjected to a period of polishing and retested for skid resistance. The limestone mixes should be given primary consideration. If the ash used in these mixes helps prevent a smooth, skid prone surface from developing after the limestone has polished, there may still be an application for limestone as a surface aggregate in areas where limestone is abundant.

7. After the polished skid test data are collected, a full-scale pavement overlay should be constructed using various aggregate-ash combinations which show the most promise as pavements.

8. Bottom ash should be sampled from the six power plants at various intervals to permit the variability of the ash at each facility to be evaluated. This would be of assistance in validating the suitability of the various sources for highway construction purposes.

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APPENDICES

APPENDIX A

Determination of Aggregate Gradation Modulus ($\bar{A}$)
and Corresponding $\Delta\Sigma\bar{A}$

Sieve Fraction	(A) A_i^*	(B) Original % Retained	(C) (A)×(B)	(D) Final % Retained	(E) (A)×(D)
1" - $\frac{3}{4}$ "	1.31	X	1.31X	Y	1.31Y
$\frac{3}{4}$ " - $\frac{1}{2}$ "	1.80				
$\frac{1}{2}$ " - $\frac{3}{8}$ "	2.31				
$\frac{3}{8}$ " - 4	3.00				
4-8	4.00				
8-16	5.00				
16-30	6.00				
30-50	7.00				
50-100	8.00				
100-200	9.00				
-200	14.00				
$\bar{A}_C = \Sigma(C) = 1.31X$				$\bar{A}_E = \Sigma(E) = 1.31Y$	

$$\bar{A} = \Sigma(A_i) \times \left(\begin{array}{l} \% \text{ by weight of each} \\ \text{sieve fraction} \end{array} \right) \quad \% \Delta\Sigma\bar{A} = \frac{\bar{A}_C - \bar{A}_E}{\bar{A}_C} \times 100\%$$

* An example calculation of A_i is performed in the ash degradation section of Chapter V.

APPENDIX B

Florida Bearing Test - Comparison of Methods
Used to Apply Initial 100 lb Levelling Load

Source - 30/50 OTTAWA SAND

Specimen	Loading Method	Load Rate lb/sec	FBV psi
I	Mechanically driven Marshall Testing Machine	14.2 47.3	9.1
II	Mechanically Driven	11.8 47.3	9.6
III	Manually Driven	17.8 35.5	10.0
IV	Manually Driven	71.0 25.8	10.8

Source - 30/50 RIVER SAND

Specimen	Loading Method	Load Rate lb/sec	FBV psi
I	Manual	15.8 23.7	13.5
II	Manual	23.7 13.5	13.7
III	Mechanical	21.8 142.0	13.9
IV	Mechanical	47.3 147.0	16.9

APPENDIX C

Design Asphalt Content by CKE Method vs. Actual Optimum
 Asphalt Content at Maximum Marshall Stability

Sample	% Asphalt (CKE)	% Asphalt (Actual Optimum)
Sand - PURDUE		
0%	5.4	6.4
10%	5.9	6.9
25%	6.8	6.8
35%	7.0	7.5
50%	8.3	8.3
Sand - PSI		
25%	5.6	5.1
Limestone - PURDUE		
0%	5.7	3.7
25%	7.0	6.0
50%	8.7	8.7
Limestone - PSI		
25%	5.7	4.7
50%	5.7	4.7

APPENDIX D

Penetration Index Determination

AP-3

85-100

Asphalt Cement

$$SP_{r \& b} = 114.8^{\circ}\text{F}; 46^{\circ}\text{C}$$

$$PTS = \frac{\log 800 - \log \text{Pen } 77^{\circ}\text{F}}{SP_{r \& b} - 77^{\circ}\text{F}}$$

$$= \frac{2.903 - (1.982)}{37.8}$$

$$= \underline{0.024}$$

$$PI = \frac{30}{1 + 40 (PTS)} - 10$$

$$= -0.602$$

COVER DESIGN BY ALDO GIORGINI